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KARST INVESTIGATIONS OF MALIGNE BASIN, JASPER NATIONAL PARK, ALBERTA

by

© PAMELA BETH KRUSE

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF GEOGRAPHY

EDMONTON, ALBERTA

FALL, 1980

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled KARST INVESTIGATIONS OF MALIGNE BASIN, JASPER NATIONAL PARK, ALBERTA submitted by PAMELA BETH KRUSE in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

ABSTRACT

Medicine Lake, located near Jasper Alberta, is an intermittent karst lake. There are two sets of sinks in the lake which feed the large inaccessible Maligne Cave system. Dye tests completed on Medicine Lake indicate that both sets of sinks have good connections at all lake levels with the Main Risings and the Hatchery Pools down-valley from Maligne Canyon. The flow-through times for the main sinks have been established to range between 11 hours at high lake levels (just 4 hours longer than surface flow) to 80 hours at low lake levels. The side sinks have flow-through times of greater than 120 hours at low lake level. These relatively fast flow-through times indicate that Maligne Cave is a very well developed system. A hypothetical cross-sectional model of the Maligne Cave is presented.

The lake bottom springs of Lac Beauvert have been proven as outputs from Maligne Cave. This discovery gives credence to the hypothesis that the cave is preglacial in age. The preglacial, well developed risings may have been destroyed by the proto-Athabasca glacier and covered with glacial sediments. The Lac Beauvert springs may represent a remnant of the buried pre-Pleistocene output.

Analysis of the Maligne River discharge hydrographs reveals the presence of a classic plateau at 42.5 m^3s^{-1} during the summer months. This plateau is representative of impeded flow. Flow may become impeded when the capacity of the sink openings themselves is reached, when the cave

channels become water filled, or when the risings are discharging at full capacity.

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1. CHAPTER ONE, THE GEOGRAPHICAL SETTING

1.1 THE PROBLEM

There are many unanswered questions about the behavior of water in a limestone aquifer despite considerable research in karst hydrology. These questions are complicated when the aquifer is inaccessible for exploration. One area of concern, for which data are scanty, is the determination of the nature, location, and level of sinks by reliable yet inexpensive methods. The underground portion of the Maligne River, in the lower Maligne Basin, Jasper National Park, Alberta, is an inaccessible system. Previous research accomplished in this region has revealed much information about the nature of the related large conduits, and this cave system is believed to be one of the largest inaccessible cave forms in the world . The previous research (Brown, 1970, see also Brown, 1972) was accomplished using methods that may be easily applied to investigations of other cave systems, such as dye tracing, geochemical analysis, and statistical analysis of hydrographs. The basic connection between the sinks of Medicine Lake and the springs along the Maligne River has been established. A water budget of the system has been completed and a cave model presented (Brown, 1972).

The present study was designed as a continuation of past work and had four main objectives:

1. to trace the two separate areas of sinks of Medicine

Lake in order to establish flow-through times to the springs at various lake levels,

2. to determine the possible connections of three spring fed lakes to the Maligne cave system,
3. to analyze discharge hydrographs of the Maligne River as compared to the hydrographs of the Miette River,
4. to present an updated model of the Maligne Cave.

1.2 Description of the Field Area

1.2.1 Topography and Geology

The Maligne River Basin is located in Jasper National Park, West Central Alberta (Figure 1). The Maligne River drains an area of 880 km^2 (340 mi^2). Altitudes in the basin range from 1000 m.a.s.l. to 3300 m.a.s.l. and there is considerable (1000m) local relief from the valley floor to the adjacent ridge tops. The Maligne River heads in the Brazeau Icefield and flows into Maligne Lake, the largest lake in the Canadian Rockies. The river then flows out of Maligne Lake and eventually into Medicine Lake where drainage usually sinks underground for a downvalley distance of 16km (10 mi). The Maligne River resurges near the downstream end of a spectacular canyon and then flows into the Athabasca River, as one of its largest tributaries. The entire Maligne Valley has been glaciated and hangs 90m above the Athabasca Valley.

The Maligne Basin consists of three valleys; the main Maligne River valley, a parallel valley named Surprise, and Beaver Valley The behavior of drainage throughout the basin is under the influence of both fluvial and karst processes. Surprise Valley drains underground through two sinking lakes and other smaller sinks. Maligne Valley has karst features as well as normal drainage throughout. Springs recently found at the north end of Maligne Lake (J. Todgham, pers. comm., 1979), the sinks of Medicine Lake, the main cave

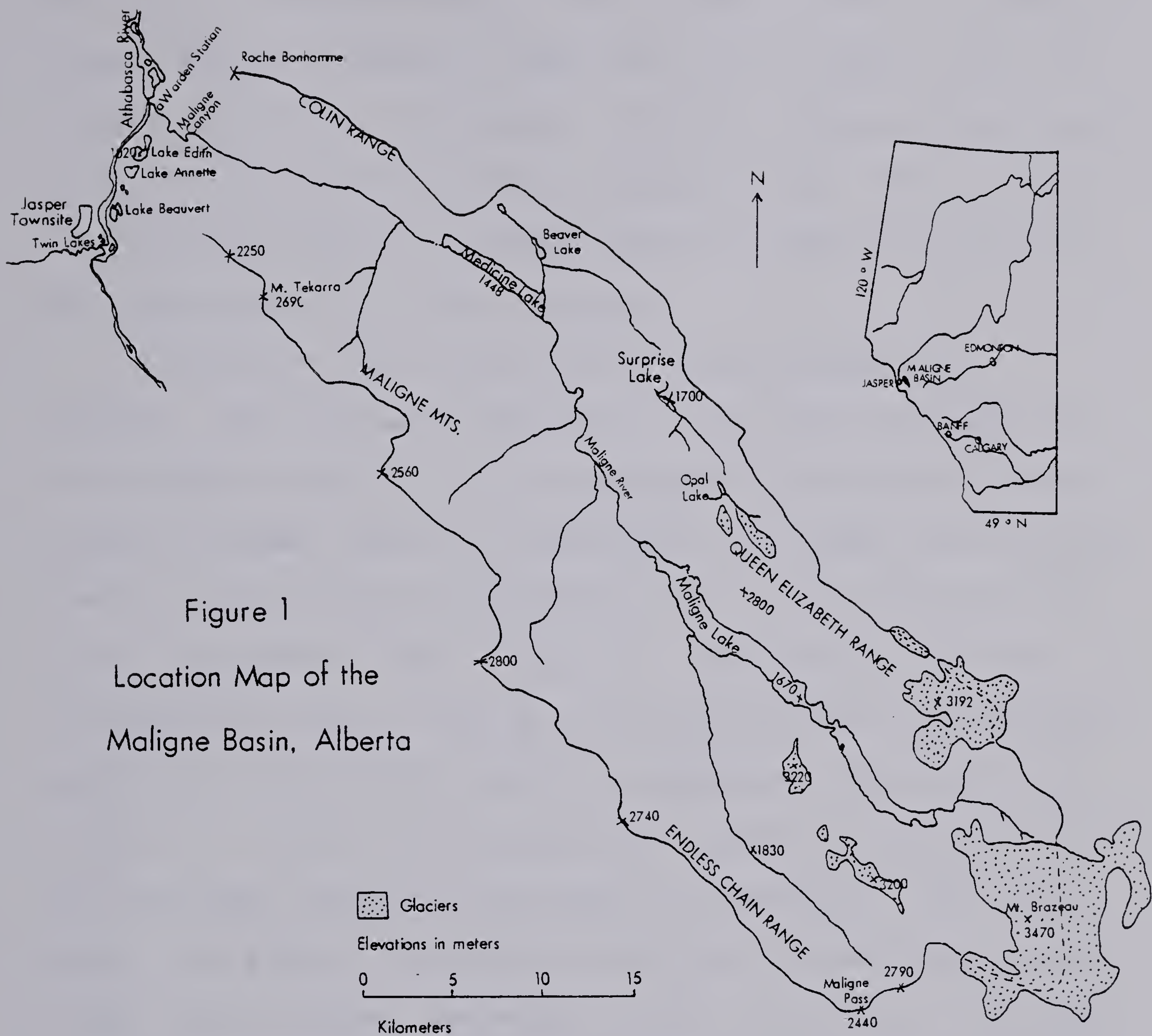


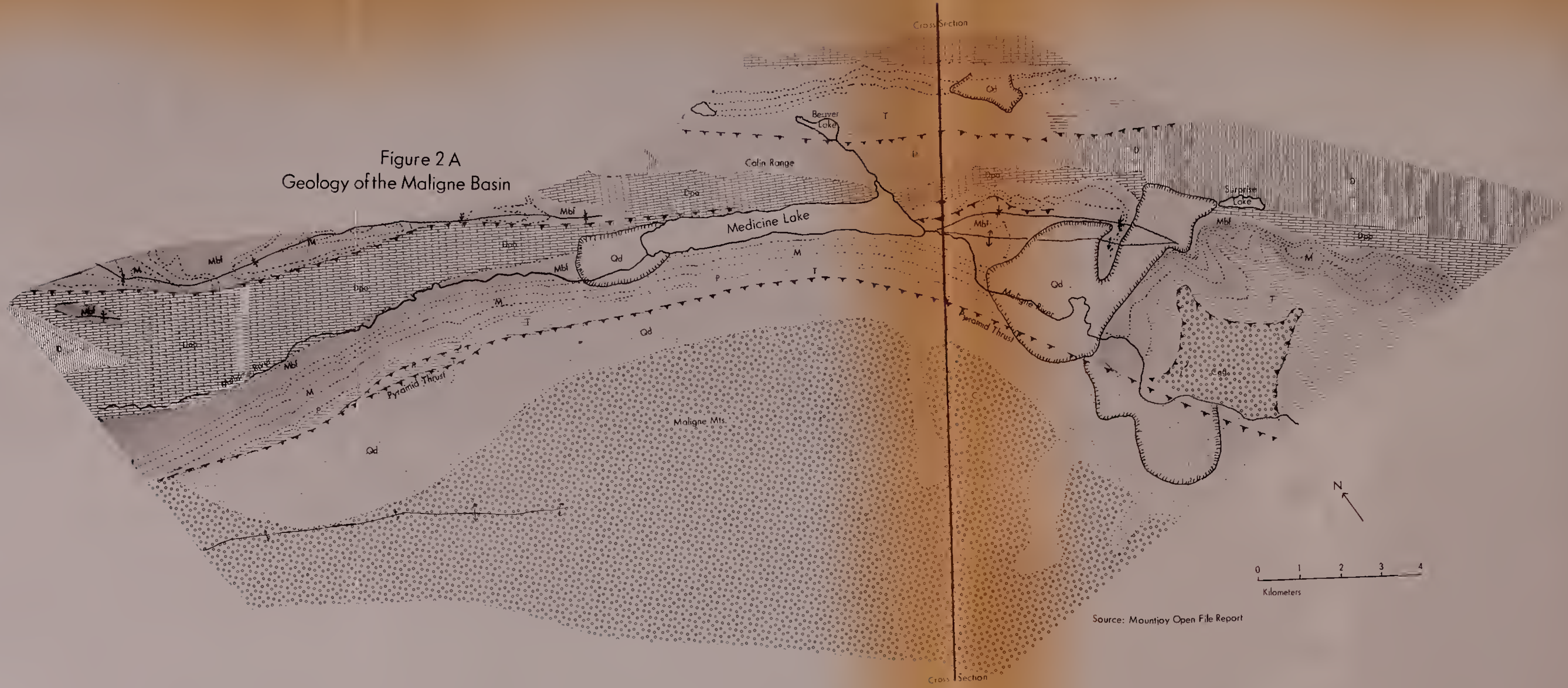
Figure 1

Location Map of the Maligne Basin, Alberta

system, and springs downvalley, all indicate extensive karst development in the main valley. Normal drainage is well developed in Beaver Valley, a tributary to the Maligne, as well as in large portions of the Maligne Valley. A series of lakes; Annette, Beauvert, Dead Man's Hole (one of the Twin Lakes), and Edith, is located along the Athabasca River just south of its junction with the Maligne River. All of these lakes are spring fed, although Beauvert seems to have the best development of these springs.

Glaciation has altered the valley considerably; however, the rocks and structure of the basin pre-date the Pleistocene glaciations. The geology of the basin has been recently mapped (maps not available in finished form at this time) and described by Mountjoy (1964, 1974, GSC open file report) and Roed (1964) (Figure 2). The oldest rocks are Precambrian in age. These are the Miette Group strata which consist of silty shales, pebbly sandstones and quartzites (Table 1). Rocks of this group are exposed on much of the Maligne Range along the southwest to northwest rim of the basin. The Miette Group rocks have been eroded and assume a lower, more rounded, secondary relief relative to the range composed of younger rocks on the opposite (southeast to northeast) side of the valley. Overlying the Miette Group are the Cambrian rocks. The oldest Cambrian unit is the Gog Formation (approximately 1220m (4000') thick), which is also exposed along the Maligne Range. The remaining Cambrian rocks consist of shales and limestones which have been

Figure 2 A
Geology of the Maligne Basin

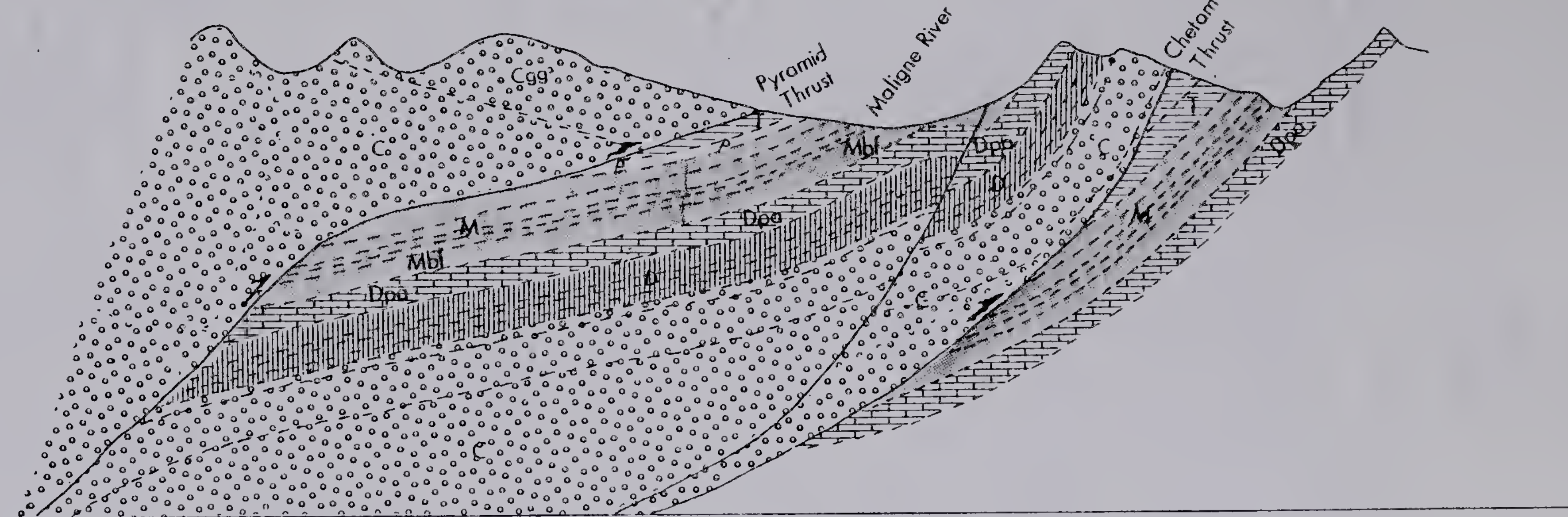


Source: Mountjoy Open File Report

Legend Figure 2

- Qd Quaternary
- T Triassic
- P Permian
- M Mississippian
  - Mbf Banff Formation
  - Dpa Palliser Formation
- D Devonian
- C Cambrian
  - Cgg Gog Formation
- Thrust Fault
- Anticline
- Syncline
- Geologic Formation Boundary
- Landslide

Cross Section Figure 2B



Vertical Scale 1:50,000

Source: Mountjoy Open File Report

TABLE I

Geologic Formations

ERA	PERIOD OR EPOCH	GROUP OR FORMATION		LITHOLOGY	THICKNESS (m)
MESOZOIC	Lower Cretaceous		Luscar Fm	Sandstone, fine grained; greenish grey siltstone; shale; coal.	610
			Cadomin Fm	Conglomerate, chert & quartzite	3 to 9
			Disconformity		
	Lower Cretaceous and Jurassic		Nikanassin Fm	Sandstone; siltstone; silty mudstone dark grey.	305 to 610
	Jurassic		Fernie Group	Shale, black and dark grey, concretionary; all members present.	213 to 274
			Disconformity		
	Triassic		Whitehorse Fm	Carbonate, light grey breccias, red mudstone, gypsum.	30 to 457
			Sulphur Mountain Fm	Siltstone, dark brown grey; thin bedded silty mudstone.	183 to 305
			Disconformity?		
PALAEOZOIC	Permian and/or Pennsylvanian		Rocky Mountain Fm	Massive grey chert; cherty brown sandstone.	0 to 67
			Disconformity		
	Mississippian	Rundle	Mt. Head Fm	Dolomite, dense, cherty, medium bedded.	76 to 122
		Rundle	Turner Valley Fm	Dolomite, brown, porous, coarse grained.	47 to 122
		Rundle	Shunda Fm	Limestone, dark grey, fine grained, thin bedded.	81 to 110
		Rundle	Pekisko Fm	Limestone, light grey, crinoidal, coarse grained, thick bedded.	35 to 91
			Banff Fm	Limestone and calcareous shale, dark brown, thin bedded.	152 to 231
			Disconformity		
	Devonian		Palliser Fm	Limestone, dark grey, massive, fine crystalline, dolomitic.	213 to 274
			Sassenoch Fm	Sandstone, fine grained; siltstone, silty shale, silty carbonates.	30 to 183
		Fairholme	Mount Hawk Fm	Limestone, brown grey, argillaceous; and brown calcareous shale.	76 to 213
		Fairholme	Perdrix Fm	Shale, black, fissile, thin limestone interbeds.	61 to 107
		Fairholme	Maligne & Fluma Fm	Limestone, dark grey, thin-bedded, argillaceous Limestone, dark brown, cherty, with stromatoporoids.	47 to 76
			Unconformity		
	Lower Ordovician		Sarbach Fm	Carbonates, cliff-forming.	0 to 243
			Chushina Fm	Limestone; calcareous shale; greenish-grey intraformational conglomerate.	0 to 213
	Upper Cambrian		Lynx Fm	Carbonates, silty, thin-bedded, argillaceous; intraformational conglomerates.	305 to 737
	Middle Cambrian		Arctomys Fm	Shale, silty, red and green; siltstone, brown.	183 to 243
			Pika Fm	Limestone, calcareous; shale, thin-bedded.	152 to 213
			Titkana Fm	Limestone, dark grey, massive dolomitic.	152 to 243
			Shale Unit	Shale, green and red; argillaceous limestone. Limestone, dark grey, resistant.	426 to 548
	Lower Cambrian		Gog Fm	Sandstone, light grey; quartz, cross-bedded, fine to coarse grained, massive.	1219
			Disconformity?		
	Precambrian		Miette Group	Shale & phyllite, grey sandstone, conglomerate	1676

Source: Mountjoy, 1974

eroded into a series of cliffs and benches along the south end of Maligne Lake (Roed, 1964). Overlying the Ordovician limestone is the Devonian Fairholm Group made up of limestones and shales. The Fairholm Group is exposed on Maligne Mountain on the north side of Maligne Lake (Roed, 1964). Overlying the Fairholm Group is the Sassenach Formation which is composed of sandstones, limestones and shales. The most important formation in the context of this study is the Palliser. This upper Devonian limestone seems to wholly contain the underground cave system of this basin. This is borne out by the fact that the water sinks and rises near the top of the formation (Brown, 1972). It is a thickly bedded (213 to 274m) massive, dense, and mottled limestone. The Palliser Formation outcrops on much of the length of the Colin Range, which runs along the northwest side of Medicine Lake to the Athabasca Valley.

The overlying Mississippian rocks are composed of the Banff Formation (dark shales) and the Rundle Group carbonates. These beds are exposed on the southwest side of the river valley from Medicine Lake to Maligne Canyon and on the ridge between Medicine Lake and Roche Bonhomme (Roed, 1964). The majority of the springs in the valley issue from the contact between the Banff and Palliser Formations.

The Rocky Mountain Formation overlies the Mississippian carbonates. This is a chert and dolomitic sandstone bed of Permian and/or Pennsylvanian age. The Triassic Sulphur Mountain Formation siltstones and sandstones cover the Rocky

Mountain cherts. The Laramide Orogeny of the Cretaceous period created the major structural features of the region (Roed, 1964). The local fold and thrust fault patterns, resulting from regional tectonism, eventually determined the NW-SE trend or strike of the valleys. The Colin and Chetamon thrusts (Figure 2) formed the steeply SW dipping ridges of the Queen Elizabeth Range on the NE side of the basin. Another major thrust sheet, the Pyramid, follows the west side of the river valley. This is related to a low angle thrust fault along which the older Precambrian and Cambrian strata were pushed onto younger Mississippian carbonates. It is quite likely that this thrust fault disrupted the rocks to contribute to the formation of the cave system (D. Cruden, pers. comm., 1979). Faulting produces cracks which the water would gradually widen, through solution and abrasion, into cave channels. The Pyramid thrust overlaps another unnamed major thrust which passes under Maligne Lake. There is considerable folding in the mountains around Maligne Lake and west of Medicine Lake.

1.2.2 Surficial Deposits and Drainage

The retreat of the Pleistocene glaciers left many glacial deposits throughout Maligne Valley. A minor readvance, after the main ice disappeared, deposited the moraine which dams the north end of Maligne Lake. The remnants of a lateral moraine are present up-valley from Maligne Canyon. This moraine diverted the path of the

Maligne River from its preglacial valley and is responsible for its present course over Palliser limestone (Mountjoy, 1974). Some ice-stagnation features are present in the valley, including hummocky moraine, kettles, deltas, and moulin kames (Roed, 1964). Large amounts of meltwater and glaciofluvial sediments formed a valley train downvalley from Maligne Lake.

An outstanding feature of the valley is the landslide at the NW end of Medicine Lake. It is composed of large blocks of Palliser limestone which fell from the steeply dipping (40°)ridge face to the north. Figure 3 is an air photo and Figure 4 is a geologic cross section of the Medicine Lake slide. The crown of the slide is close to the hinge of an anticline and Cruden (1976, p. 15) suggests that the scarp originally followed the strike set of joints which formed perpendicular to bedding and the scarp has since retreated.

Present drainage down the landslide scar surface collects in two small poljes at the foot of the slide. These may sink into bedrock and join the cave system from Medicine Lake.

There has been some controversy as to the origin of the landslide and its relationship to Medicine Lake and the sinks. The landslide is post-glacial in age (Cruden, 1976) and is believed to have been triggered by glacial undercutting (Roed, 1964) or perhaps by sink sapping at the base of the cliff (Ford, 1968). It had been suggested that

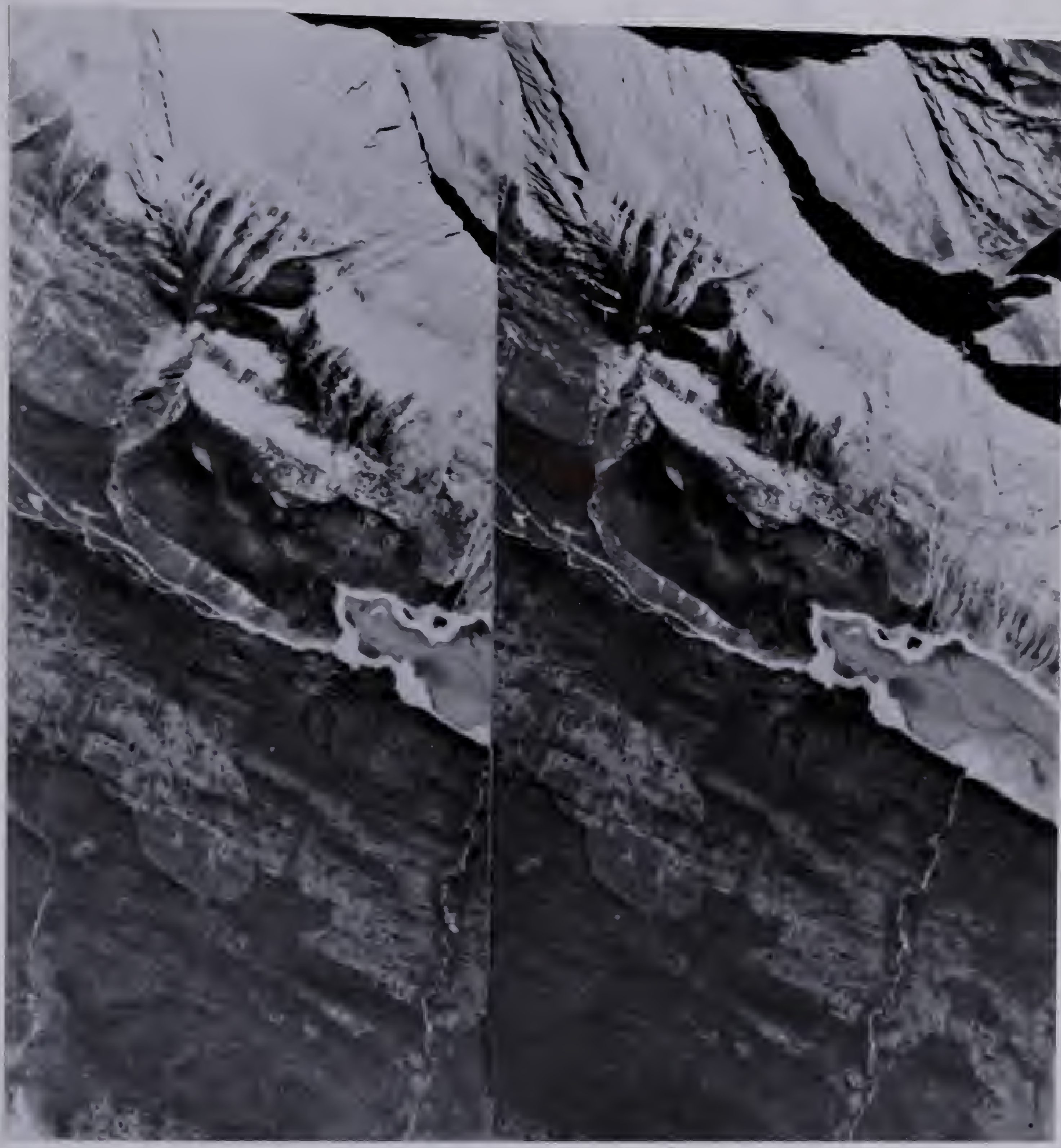


Figure 3

Air Photo Stereopair of the

Medicine Lake Landslide

Alberta Government Photo AS-160-5220X-1472-16,17
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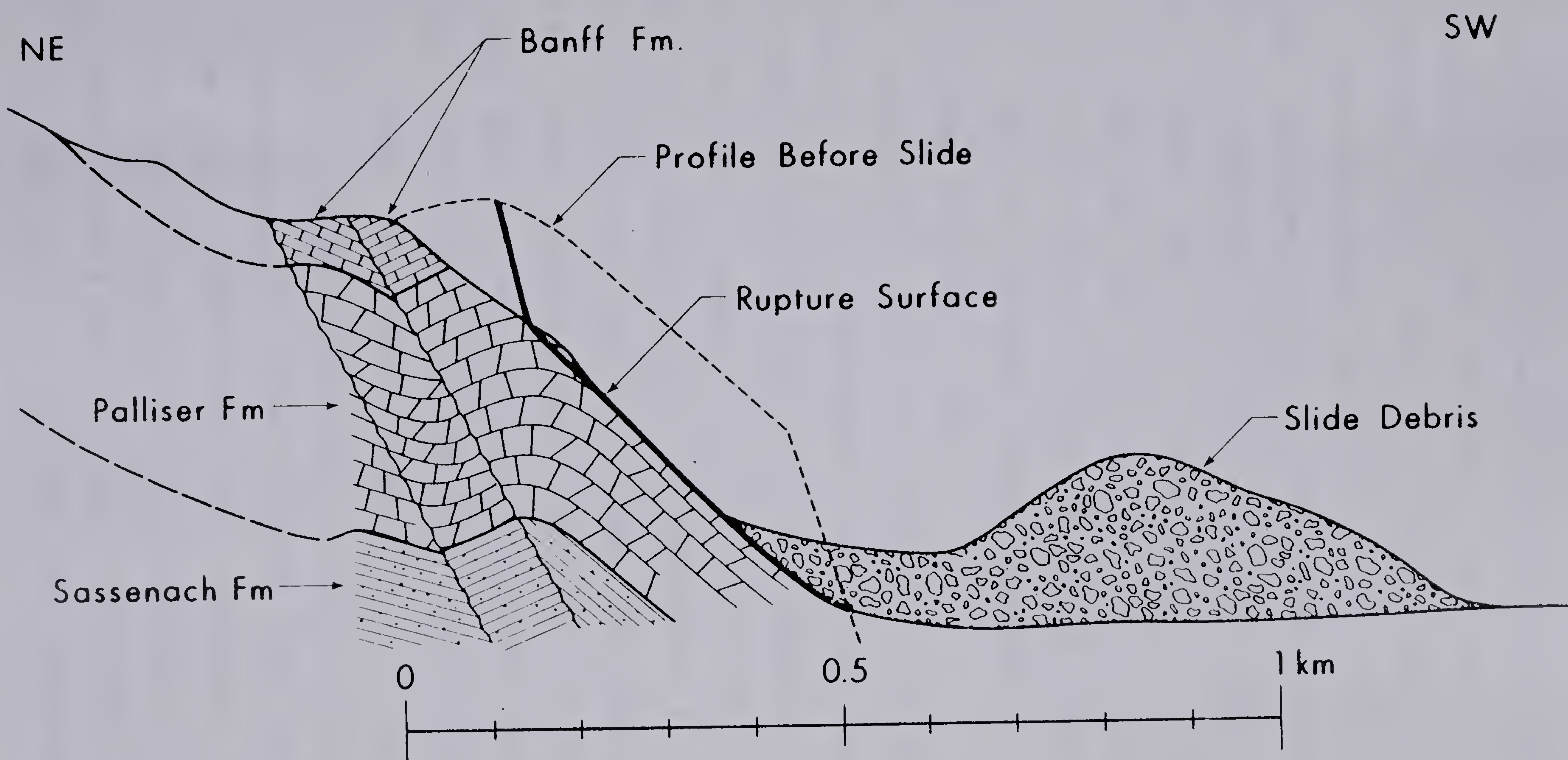


Figure 4

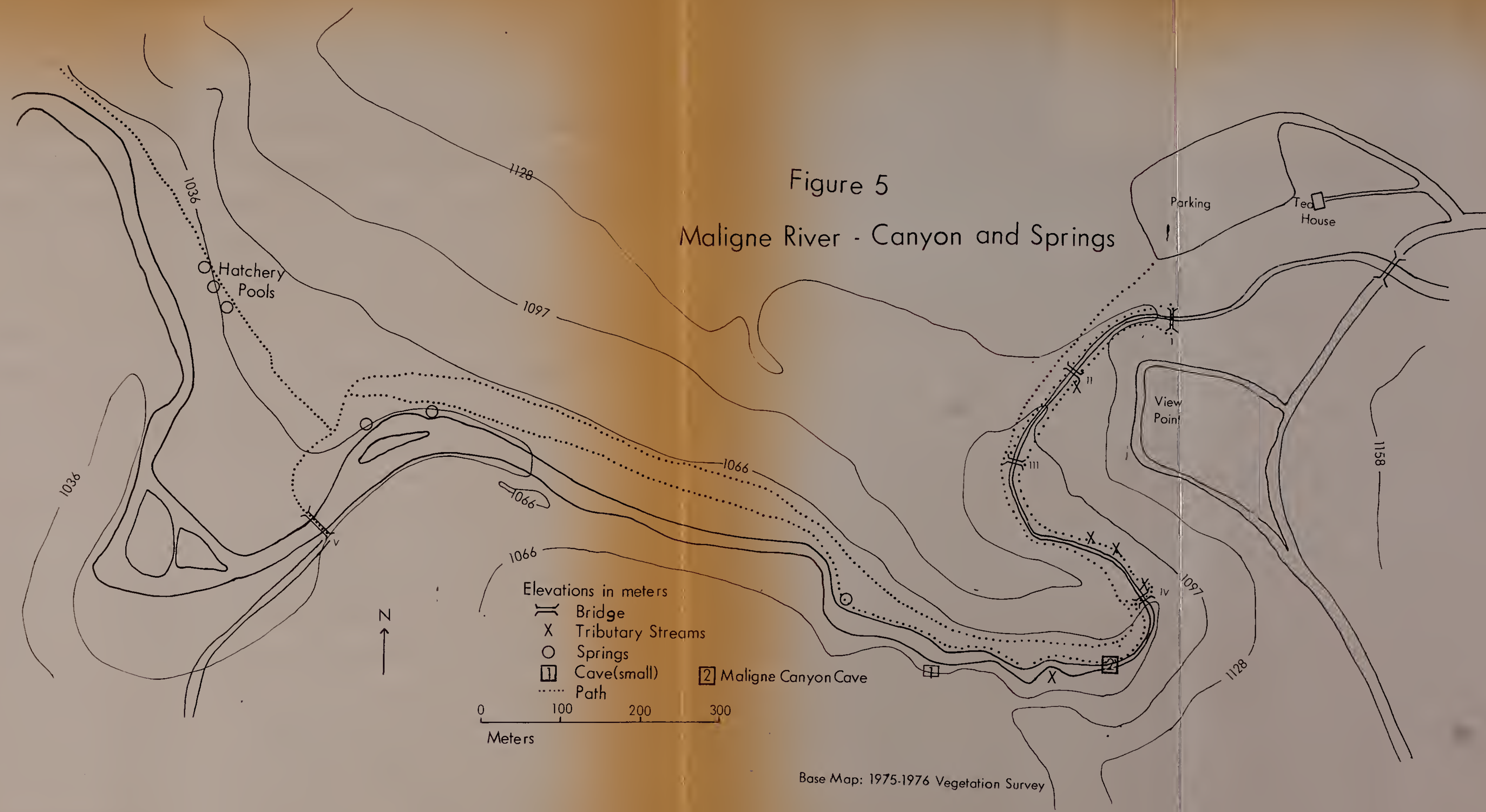
Geologic Cross Section of Medicine Lake Landslide Source: Cruden, 1976

Medicine Lake was dammed by these avalanche boulders and the sinks were generated through this debris (Edmonton Geological Society, 1964). There is little evidence that the slide debris would have been impermeable to drainage from Medicine Lake. At present the water sinks through the debris and an overflow channel has been cut through the debris and into bedrock to drain the lake at flood times. For these reasons it is concluded that the landslide did not generate the sinks of the lake where none existed before (Brown, 1972), but in fact the cave and sinks are probably preglacial and pre-landslide in age.

Another outstanding feature of the basin is Maligne Canyon (Figure 5). It is a spectacular, pot-holed gorge cut by solution and abrasion into the Palliser limestone. It is entrenched 90m into the hanging threshold of the Maligne Valley above the Athabasca Valley. It descends this elevation over less than 2.7km in distance. The upper two thirds of the canyon extends in an E-W direction following a regional joint pattern. From 1st Bridge to 2nd Bridge, the canyon drops nearly 50m in elevation over 100m in distance. Approximately 30m of this vertical drop is in a series of spectacular falls. In the middle section (2nd Bridge to 3rd Bridge) the stream gradient becomes gentler. The lower portion of the canyon (3rd Bridge to 4th Bridge) swings southward to follow an intersecting joint pattern. It is along this section that a series of small tributary streams flow out of the east wall of the valley into the canyon

Figure 5

Maligne River - Canyon and Springs



Base Map: 1975-1976 Vegetation Survey

gorge. These flow out of surface deposits all seasons of the year. In winter they form spectacular ice falls in the canyon.

Downvalley from 4th Bridge the canyon returns to the general E-W trend and here the main springs enter the river. The largest springs flow from the south wall, issuing from small caves generally inaccessible for exploration. There are two exceptions (Figure 5). One ('small') which extends for approximately 100 meters ending in an impassible wall. The second, termed the Maligne Canyon Cave, (Thompson, 1975, 1976) is entered through a tight sqeeze of approximately 30 meters of wide bedding plane. This opens into "The Big Room" which is 5m high, 2m wide, and developed along a joint. Passages leave this chamber on three levels. One leads to a "Stalactite Grotto" developed in the Banff shale at the roof of the chamber. The other two passages connect and lead through breakdown to a 30m descending passage of wide bedding plane which eventually narrows. The cave was surveyed and mapped (Thompson, 1976) and found to be 373m long and extending down valley from the rising at the surface. Exploration of this cave demonstrated the water rises from great depth but did not give access to the main cave. It is possible the whole system is a series of wide bedding planes and no master cave exists.

The smaller springs flow out of fissures and joints. There is another set of springs, to the north of the river (Figure 5) called the Hatchery Pools (Brown, 1972). These

are approximately 18 meters lower in elevation than the Maligne River springs.

1.2.3 Climate

Some precipitation and temperature data are available for the basin for the years 1969 to present (W. Pfiesterer, pers. comm., 1979). A meteorological station is situated at the Maligne Lake Warden Station and manned by the year-round Maligne Lake Warden. The mean monthly temperatures range from -15°C in January to 13°C in July. The mean annual temperature is -1°C. The mean maximum monthly temperature ranges from 18°C in August to -10°C in January and averages 5.5°C. The mean minimum monthly temperature ranges from -30°C in January to 3.4°C in August and averages -7°C. Table 2 presents basic climate data for the basin.

Brown (1972) states that precipitation in the basin seems to be largely a function of altitude. The mean rainfall for six temporary stations at various locations (Figure 6) demontrates this conclusion. The mean rainfall for all six stations for the period May 17 to August 30, 1968 was 176mm while Jasper Townsite received 163mm over the same period.

The Maligne Lake precipitation data (for the years 1969 to 1979) show the region to be semi-arid with precipitation varying from 68mm in June to 15mm in October. The mean total precipitation is 442mm per year. Depth of snow on the ground data are available for the years 1969 to 1972. The snow

TABLE 2

Climate Statistics,1969 to 1979

Mean January Temperature	-15.0°C
Mean April Temperature	- 0.5°C
Mean July Temperature	13.0°C
Mean October Temperature	3.5°C
Mean Spring Precipitation	26.3 mm
Mean Summer Precipitation	49.0 mm
Mean Autumn Precipitation	28.3 mm
Mean Annual Snowfall	76.0 mm
Total Annual Precipitation	441.6 mm

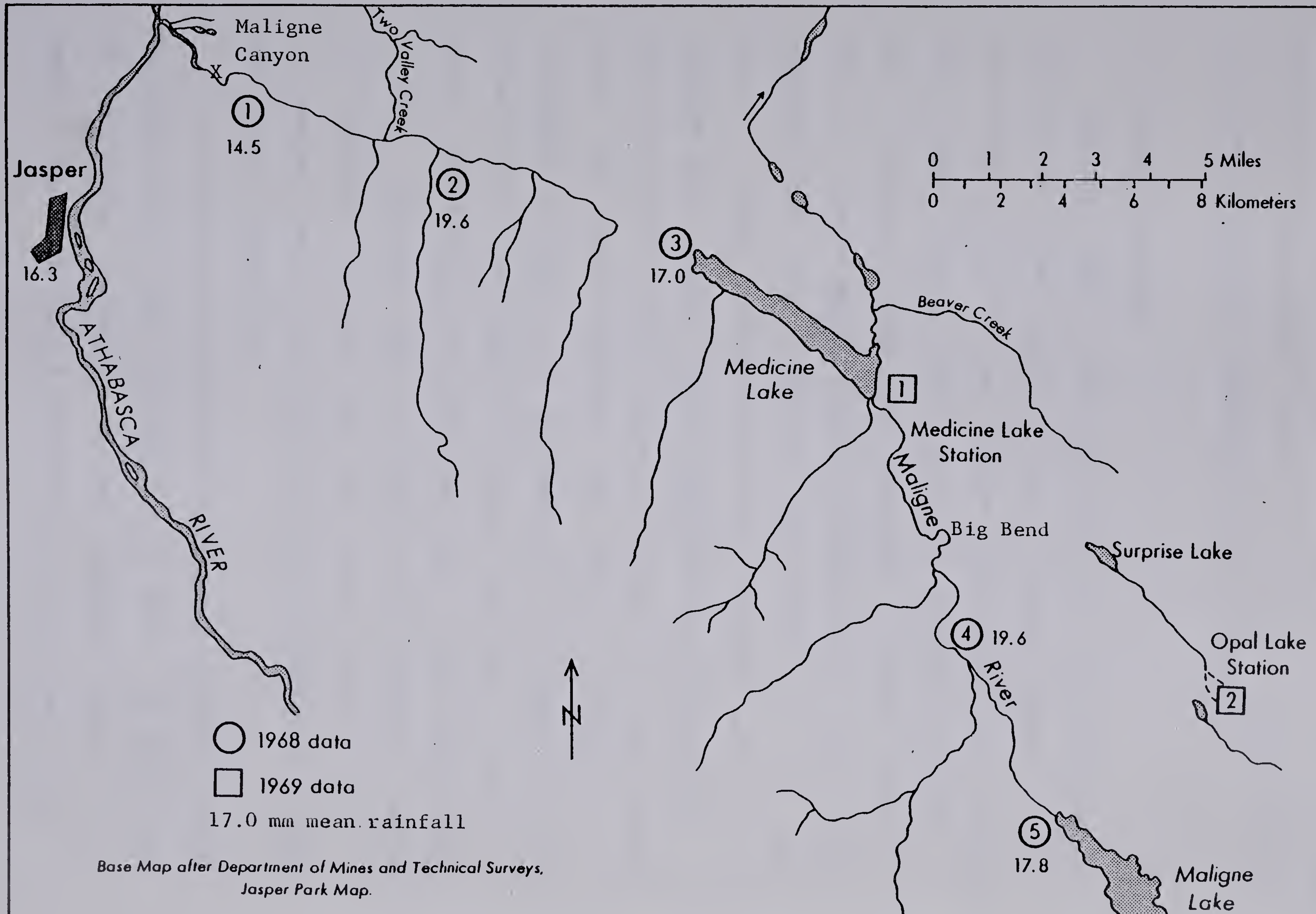


Figure 6 Rain Gauge Locations Source: Brown, 1972

depth increases from an average of 40mm in October to 760mm in March. Precipitation data on individual storms will be discussed along with hydrograph data in Chapter 3.

1.2.4 Medicine Lake

Medicine Lake is the main sink into the underground cave system. There are two areas of sinks (Figure 7). The main sinks are at the northwestern end of the lake. Here the water sinks through landslide rubble at many locations. A small tributary stream sinks here also. Another area of sinks is located approximately halfway up the lake on the northern side. These sinks are only visible when the lake level is low but are active at high levels as well. J. Todgham (pers. comm., 1979) reported that flow can be observed and felt while scuba diving over the side sinks at higher lake levels. Medicine Lake levels fluctuate throughout the year. The lake when full is 7km long, up to 0.8km wide and 18m deep at its overflow level. In early spring, discharge of the Maligne River is low, approximately 1.5 m^3s^{-1}, and the lake is virtually non existent. The main river meanders through a mud flat to the sinks at the northwestern end while a distributive stream flows to the side sinks (Figure 8a).

As discharge increases during the spring melt period, the sinks do not have the capacity to drain the water and the lake fills. It remains a lake throughout most of the summer (Figure 8b). As a combination of snow melt, glacial

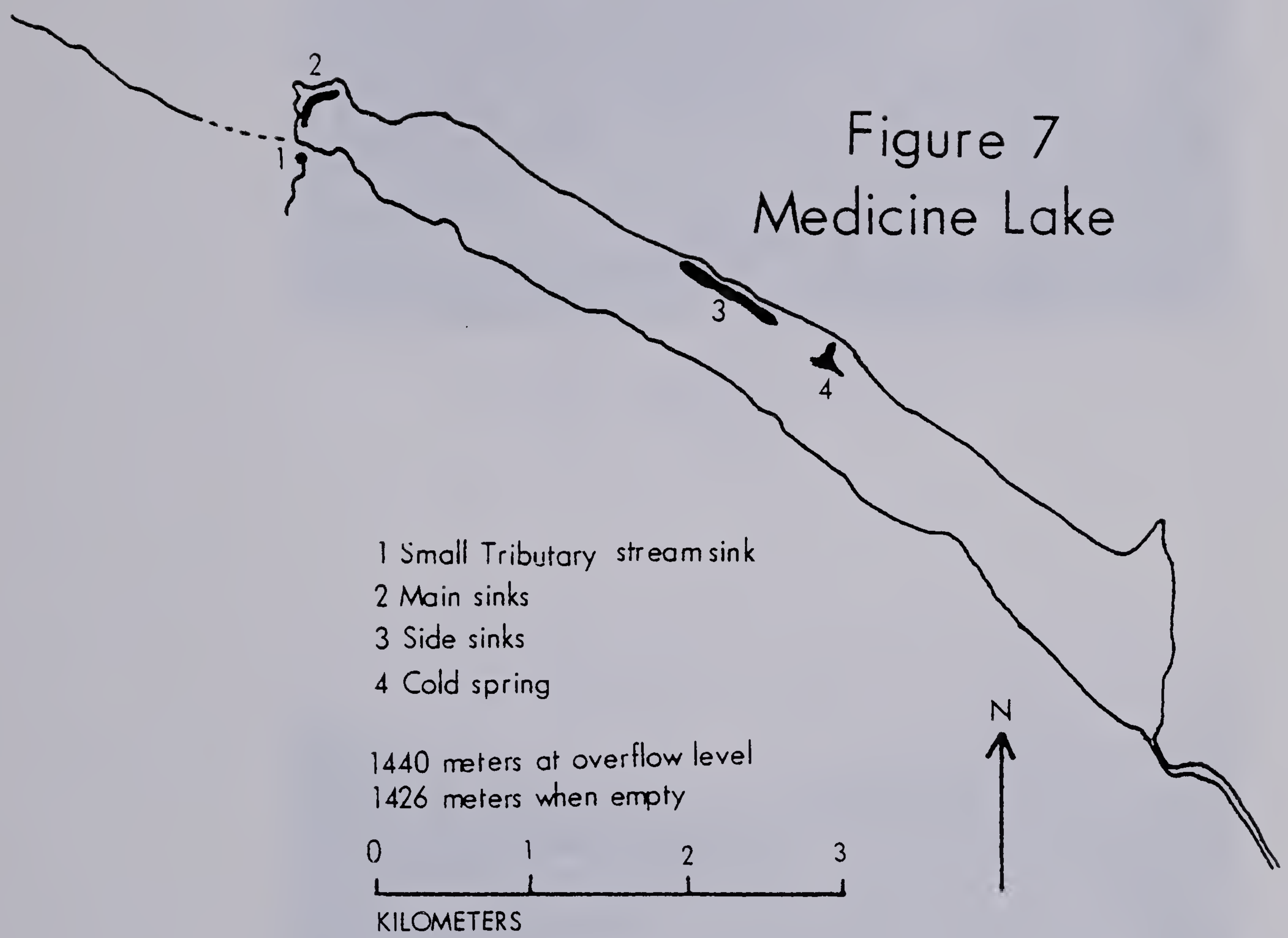


Figure 7
Medicine Lake

(a)

Medicine Lake at low level
(by J. Todgham)

(b)

Medicine Lake at nearly high level
(by D. Huddlestone)

Figure 8

ice ablation and rainfall declines, discharge of the Maligne River decreases and the lake level drops as it drains through the sinks. By late fall the lake has emptied and the river meanders through the lake bottom mud flats until the cycle begins to repeat itself the following spring.

Lake level data are now recorded weekly by the Maligne Lake Wardens. These data are read, from the road, with binoculars off poles installed in 1975. The lake level may become high enough to overflow. Sketchy data are available on high lake levels, beginning in 1947 (Appendix 1). During the years 1947 to 1979 Medicine Lake overflowed nine times. The date of highest lake level each year ranges from June 14 to August 10. The lake has also overflowed twice in the same year (1948). It has been concluded (Brown, 1972) that high lake level can be modelled or predicted by previous springtime temperatures, specifically, average daily maximum temperatures for May. In other words the high lake level is a result of the rate at which the snow melts, not total precipitation. For example, during a particularly cool spring, in which May temperatures are low, snow melt is delayed until late June or July and the result of rapid melt will likely be an overflow period for Medicine Lake. Conversely, if May temperatures are warm, and the snow melts gradually through spring and summer, there will be no overflow. This is obviously dependent to some extent on amounts of precipitation. During the 1979 field research period there were low May temperatures, but the preceding

winter experienced low snowfall amounts. Thus the lake rose to just over half its normal "full" capacity following the relatively meagre snowfall recharge.

1.3 Previous Studies of the Maligne Basin

Attempts to understand the disappearance of the Medicine Lake waters and to discover their destination date to the 1930s. The first interested investigator, Mr. M. McGuire, dumped two truckloads of used magazines in Medicine Lake in an unsuccessful attempt to find the destination of the disappearing water or to stop the flow altogether. In 1956 Corbel, a French geomorphologist, briefly visited the basin and observed that water sinks in the mountains above Maligne Canyon and resurges in the canyon below, apparently through short inaccessible caves. He incorrectly considered the region to be youthful, underdeveloped karst and made no connection with Medicine Lake (Corbel, 1958, from Brown, 1972). The 1964 field trip guidebook of the Edmonton Geological Society presents an inaccurate interpretation of the destination of the water in Medicine Lake. Underground caves of any magnitude were not suspected and the guidebook states that the water travels under the landslide debris for just 0.8km (0.5mi) before resurging. Roed (1964), studying the geology and Pleistocene history of the Maligne area, was the first to correctly explain the source of the Maligne Canyon springs as being "at least in part" water from Medicine Lake. Baird (1966) restated the same general

conclusion.

In 1966 Ford and other researchers from McMaster University conducted the first successful tracer test on Medicine Lake and proved the previously hypothesized connection. This trace, using Rhodamine B dye, provided the first indications about the magnitude and complexity of the system. A large field party returned in 1967 with the purpose of finding cave openings, to allow physical access to the system. This intensive and systematic exploration proved fruitless (Brown, 1972). Geologic mapping was completed and solution measurements were taken. A second trace of Medicine Lake, using fluorescein, was unsuccessful. This was probably because fluorescein is less detectable than Rhodamine (as it decays quickly in sunlight) and the lake was at a high level, which would cause greater dilution of the dye. Tests in Surprise Valley (Ford, 1968) established what was thought to be a connection between Surprise and Opal Lake's sinks and springs along the Maligne River at the Big Bend (Figure 6). Ford suggested a flow-through time of 3-5 days. However this test was not conclusive (Brown, pers. comm., 1980) and further research is required to locate the Surprise Valley risings.

Brown (1972) studied the basin for two field seasons in 1967 and 1968. Two successful traces, using Rhodamine WT, were completed and will be discussed along with recent results in Chapter 3. Brown (1972) also used detailed statistical analysis to study the input-output hydrographs

of the cave. On the basis of analysis of the cave 'pulses' he concluded that two types of inputs exist. One known input (Medicine Lake) contributes from 30% to 100% of the input and has a pulse-through time of 70-124 hours during May's low flow volumes. Many smaller tributaries contribute from 0% to 70% of the output and have a very fast flow-through time. This lag time indicates that the cave is vadose ie. partially water filled, because if it were totally water filled, the pulses would travel almost instantaneously through the cave. This is because water is incompressible therefore, input in a water filled cavity produces shock waves which travel approximately the speed of sound.

Brown (1972) also investigated the theory of karst flow networks in relation to the Maligne-Medicine Lake system, and stated that all karst hydrologic systems that have discrete inputs and discrete outputs fall into one of five types (Figure 9). By combining this information with tracing, it is possible to calculate the budget of a system with the following calculations:

Q=Input flow rate

q=Output flow rate

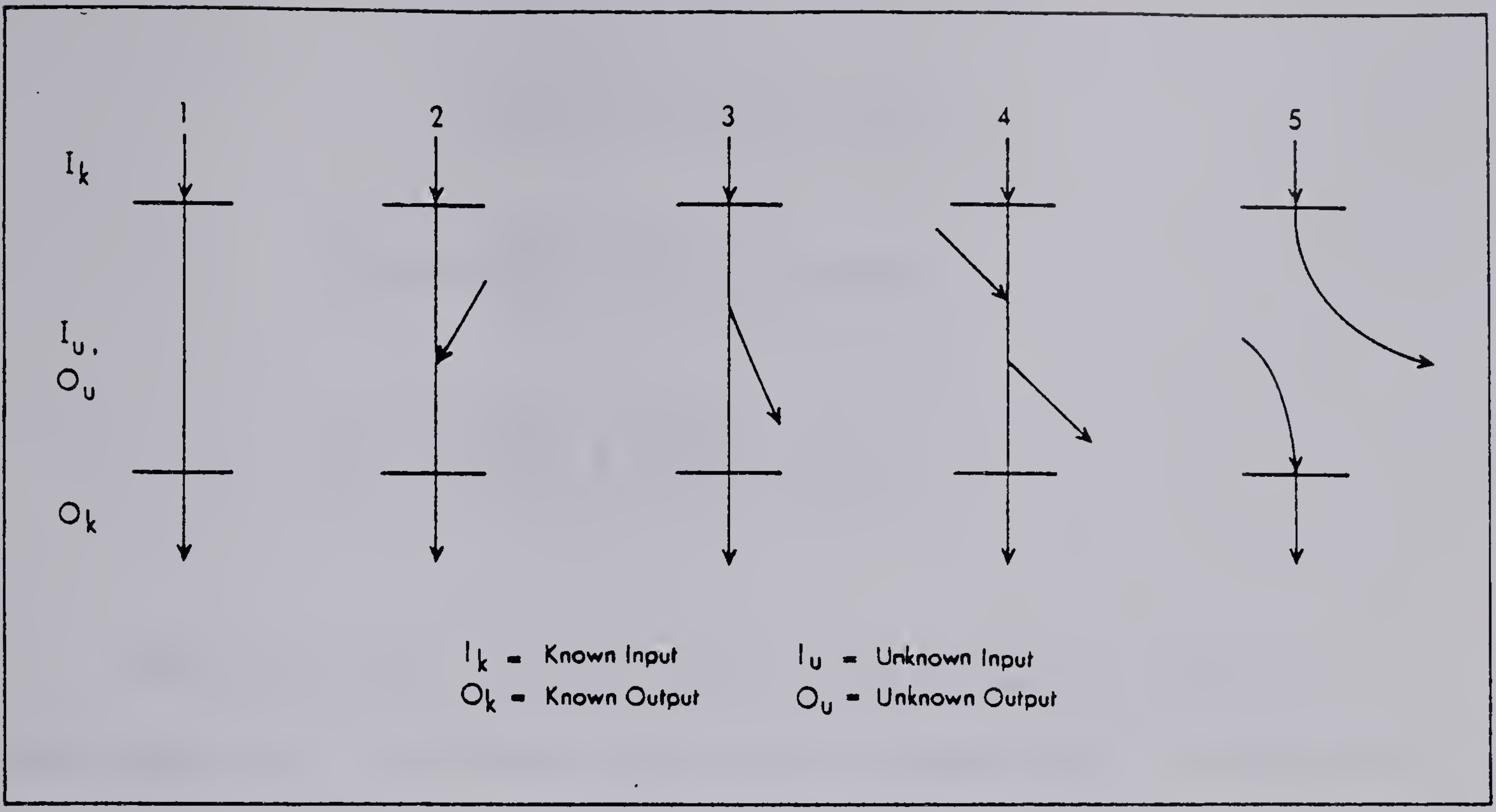
D=Injected tracer mass

d=Recovered tracer mass

With $A \supset B$ reading : If A, then B;

and $A \cdot B$ reading : Both A and B

$$[d=Q] \supset \text{Type } 5$$



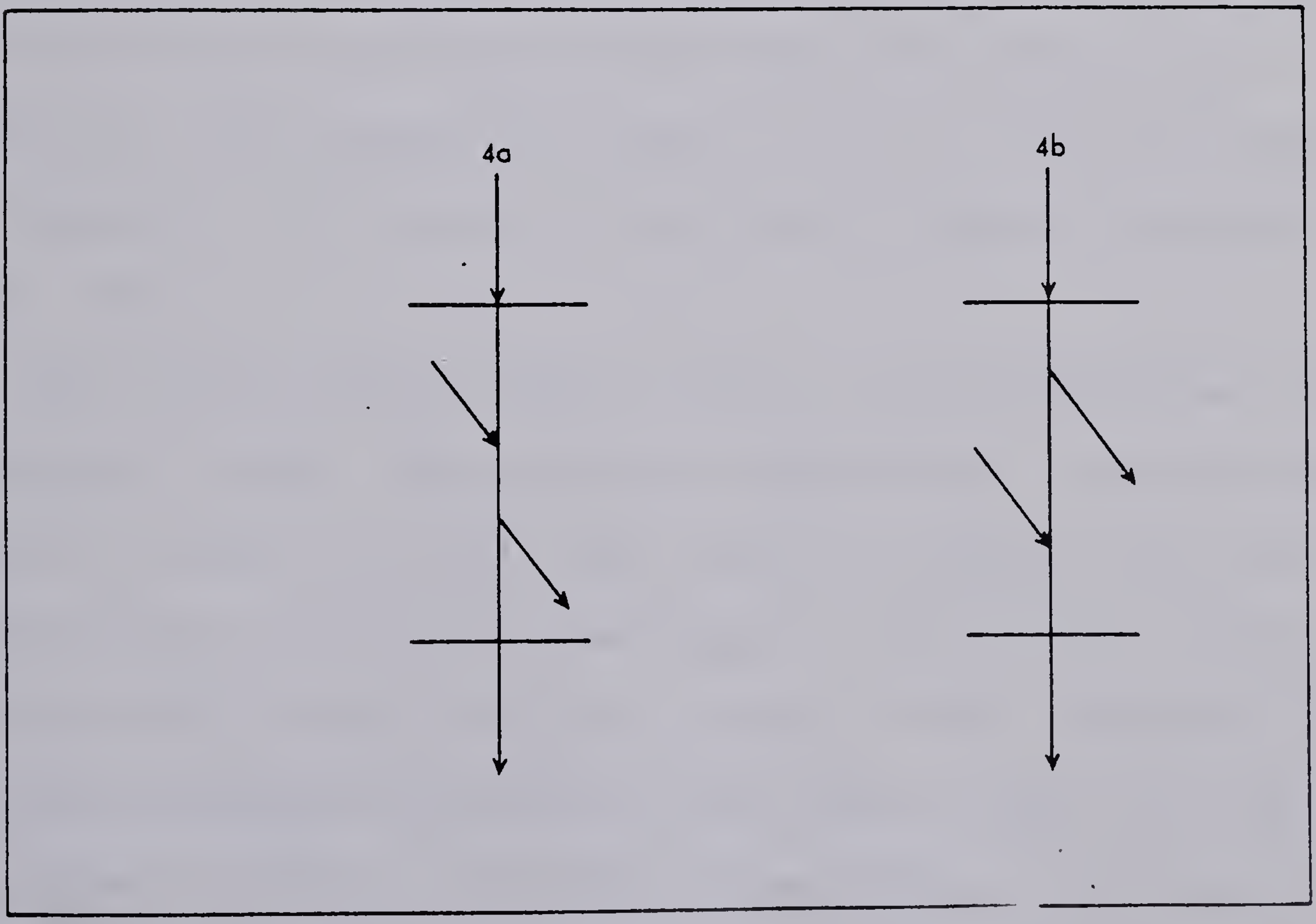


Figure 9

Karst Flow Networks

Source: Brown, 1972

$$\left[(d=D)\cdot(Q=q)\right]\supset \text{Type 1}$$

$$\left[(d<D)\cdot\left(\frac{Q-q}{Q}=\frac{D-d}{D}\right)\right]\supset \text{Type 3}$$

$$\left[(d<D)\cdot\left(\frac{Q-q}{Q}\neq\frac{D-d}{D}\right)\right]\supset \text{Type 4}$$

When physical exploration had failed to find an entrance into the cave two other methods were attempted. In hope of finding a subsurface chamber close enough to the surface to be excavated, a resistivity survey was completed which revealed an anomaly that was expected to be an air filled cavity within 45m of the surface. A drilling program was undertaken in May 1971 to locate this possible chamber. Seven holes were drilled crosscutting this resistivity anomaly but unfortunately no cavity in the limestone bedrock was revealed. The nature of the anomaly remains a mystery (Ford, 1971).

The second method used to find a cave entrance was that of thermal imagery. Because cave temperatures are relatively stable all year, air vents may show up as warmer than the surroundings in winter on the imagery. No such air vents were detected during this study (Brown, 1972). However, a previously unknown cold spring that enters Medicine Lake was discovered (Figure 7). To date, no entrances to the main system have been found so Maligne cave must be investigated

by remote methods such as tracing and hydrograph analysis.

The present study is the result of field work and research completed by the author in the summer and fall of 1979. Dye tracing was completed on Medicine Lake at various levels, testing the two sink areas both together and separately, with the purpose of establishing flow-through times and determining any new outputs to the system. The results and interpretations of these tests are contained in Chapter 2. Chapter 3 presents an analysis of discharge hydrographs of the Maligne River, which is under the influence of the cave, as compared to the non-karstic Miette River.

2. CHAPTER TWO, TRACER TESTS OF KARST HYDROLOGIC SYSTEMS

2.1 Review of Tracers in Karst Groundwater Studies

Tracing has become an extensively used method of investigating karst groundwater systems. It involves labelling the water with a tracing substance so that it may be identified later in time and at a different place in the system.

2.1.1 "Ideal" Tracer Qualities

Brown and Ford (1971), as well as Back and Zoetl (1975), list the qualities of tracers as an aid in choosing the tracer best suited for a study. An "ideal" tracer is one which will not be adsorbed any more or less than the host water by material with which it comes in contact. It should not disintegrate in water and its density should equal the density of water. Also, it should not be filtered by material present in the host water. These qualities are termed primary, as they relate to the physical and chemical properties of the tracer relative to the host water.

Secondary qualities are those of pragmatic and environmental concern. An "ideal" tracer should be non-toxic and inoffensive. It should be easily recoverable in low concentrations and be simple to analyze. Additionally, it should be precisely identifiable (little natural background masking the tracer) and at the same time sub-classifiable so that many tracers may be used simultaneously. Finally, an

ideal tracer is inexpensive.

No available tracer possesses all these qualities. There are many tracers used and each has its own set of advantages and disadvantages. These must be evaluated in relationship to the characteristics of the study area and the best tracer chosen.

There are many comprehensive reviews of tracers available in the literature. Back and Zoetl (1975) present one of the most recent and thorough reviews available. They summarize the application of geochemistry, isotopic methodology and artificial tracers to the investigation of karst hydrology. Brown and Ford (1971) present a useful table for quick comparison of the major tracers in use (Table 3). Drew and Smith (1968), Drew (1968) and Elrick and Lawson (1969), also present basic reviews of the available tracers for use in karst hydrology.

2.1.2 Dyes

Fluorescent dyes are some of the most common tracers in use today. Wilson (1968a) and Smart and Laidlaw (1975) outline descriptions of these dyes as well as methods for their use and analysis. There are four main fluorescent dyes, Rhodamine WT, Rhodamine B, Pontacyl Pink and Fluorescein (Wilson, 1968a). These are good tracers because they are water soluble, highly detectable, harmless in low concentrations and inexpensive. They are also reasonably stable in use and relatively uncomplicated to analyze.

TABLE 3

Qualities of Tracers most used in Karst Systems

	Primary Qualities			Secondary Qualities				
Tracer	Disintegration	Sorbtion	Filtering	Background	Detectability	Ease of Analysis	Quantifiable	Public Health Hazard
1) Fluorescein	Severe in sunlight	little	no	Severely masked by *Chlorella*, etc.	$1 : 2 \times 10^{10}$	simple	yes	no
2) Pyranine	?	probably very little	no	?	?	simple	yes	no
3) Rhodamine B	no	severe	no	nil	$1 : 2 \times 10^{10}$	simple	yes	Carcinogenic none at concentrations used (less than 10 ppb)
4) Rhodamine WT	no	less than 1) and 3) may be severe	no	nil	$1 : 2 \times 10^{10}$	simple	yes	
5) *Lycopodium* Spores	?	?	yes	nil with dyed spores	? not good	Time-consuming	no	no
6) Tritium	Half-life of 12.3 years	not severe	no	masked by bomb and natural variation	$4 : 1 \times 10^{18}$	very complicated & time-consuming	yes	yes
7) "Pulses"	N.A.	N.A.	yes	yes	N.A.	simple	possible	no

N.A. - not applicable

Source: Brown and Ford, 1971

However, there are serious disadvantages to these dyes. Rhodamine B has the strong disadvantage of being carcinogenic. It also has strong adsorptive tendencies. Scott, Norman and Field's (1969) work revealed sorptive loss caused by fine sediment in the banks and bed and also suspended sediment in the water system. This serious disadvantage, as well as optical quenching (scattering of light by suspended sediment)(Feuerstein and Selleck, 1963), can be minimized by allowing natural sedimentation or by centrifuging. Filtering should never be tried because filter materials may adsorb the dye causing further loss.

Fluorescein can not be used effectively for surface water tracing because it is quickly destroyed by sunlight (50% in three hours, Feuerstein and Selleck, 1963) although it is effective in underground streams. There may also be background problems present with Fluorescein as the bacteria Chlorella fluoresces near its frequency (Brown, 1972). Of the dyes available for tracing, it appears Rhodamine WT has the best balance of high detectability, low sorptive tendencies, good diffusivity and low cost.

Wilson (1968a) and Feuerstein and Selleck (1963) discuss five major factors which affect fluorescence. These must be taken into account when data are analyzed. First, fluorescence varies directly with dye concentrations. Second, the sample temperature is also a factor. Fluorescence increases as temperature decreases. Third, the pH value of the sample affects fluorescence intensity. For

example, the fluorescence of Rhodamine WT is stable in the pH range of 5-10, but decreases outside those limits. Fourth, fluorescence intensity can also be quenched by chemicals, such as chlorine, present in the host water. Finally, a permanent reduction in fluorescence may be caused by photochemical decay through bright sunlight and biological degradation.

In contrast to these dyes, which may produce visible coloration of the risings, are the optical brighteners (Glover, 1972). These were developed to bleach or brighten cotton fabrics and although colorless in daylight, they adsorb ultra-violet light and fluoresce at the blue end of the visible spectrum. They have a strong attraction to cellulose; therefore, cotton wool may be used as a detector. They are non-toxic, and easily decompose in sunlight when in solution. They are detectable in dilutions of less than $1:10^6$ and are cheaper than the commonly used dyes. Glover (1972) outlines the methodology for use and analysis of optical brighteners.

2.1.3 Spores

Lycopodium spores are another tracer in common use. *Lycopodium clavatum* is the spore of a club-moss. They are nearly spherical, have a cellulose structure, and are about 30 microns in diameter. They are fairly indestructable and have a density close to that of water (Atkinson, 1968). In tracing, the spores are trapped in conical plankton nets at

the risings and filtered out of the water for analysis. This method is advantageous because simultaneous testing of many sinks is possible by dying spores different colors. Successful colors are Malachite Green, Bismark Brown, Magenta, Saffranine Alpha, and Methyl Violet (Drew, 1968). Spore tracing is also free from background because dyed spores do not occur naturally.

Spores have the disadvantage of being easily filtered. They also have been shown to travel faster than mean water velocity due to a density slightly less than normal stream water (Brown and Ford, 1971). Also, analysis is time consuming. Other disadvantages are that the plankton nets may become clogged with sediment or torn by fast flowing waters. Contamination is also possible as just one spore can demonstrate a positive test but as they are not visible to the naked eye, they may be transported by personnel. Atkinson (1968) demonstrates that the lycopodium method is successful in providing information about underground stream connections and may contribute to building models of drainage systems.

2.1.4 Radioisotopes-Tritium

Tritium (a radioisotope of hydrogen), as an example of radioisotopes, is another major kind of tracer used in karst investigations. It possesses many of the qualities of an "ideal" tracer (Brown and Ford, 1971). It behaves exactly as the water into which it is injected, it is easily detectable

and inexpensive. However, it is not always the best tracer to choose because nuclear testing has created background interference. Also, analysis is complex and time consuming, requiring complicated and expensive equipment. Perhaps the most important disadvantage is the health hazard involved if the labelled water gets into the public drinking system. Ault and Hardaway (1965) explain the methodology of sub-surface tracing with radioisotopes. Carlston (1964) reviews some of its problems and limitations.

Burden demonstrates the successful use of tritium for tracing ground water in Greece for distances up to 30Km. A study of Lake McMillan in New Mexico (Reeder, 1963) reveals the disastrous results possible with tritium tracing. After raising the level of the lake from 40-50 tritium units to about 2,200 tritium units, not more than 100 tritium units were sampled at any of the suspected risings. The test failed in its intended purpose of showing tritium to be an effective groundwater tracer and, as well, much of the tritium labelled water, a dangerous substance, was lost in the karst system.

Other radio-isotopes in use in addition to tritium are carbon-14, uranium, and silicon-32. Stable isotopes in use are deuterium, oxygen-18, sulfur and helium. Back and Zoetl (1973) review successful studies using all of these.

2.1.5 Hydrologic Applications

There are numerous hydrologic applications of tracing.

Wilson and Forrest (1964) and Wilson (1968b) examine the use of fluorescent dyes in "time-of-travel" studies, or the description of the downstream movement of water with time. They find that dye tracing reveals accurate estimates of mean travel times and information about the longitudinal spread and decrease in concentration as dye in solution travels downstream. Fischer (1968) also writes about this dispersion of dye in natural streams.

A study by Replogle, Myers et al., (1966) outlines a method of using tracers to measure discharge. This is efficient and accurate and particularly useful in areas where other gauging methods are not available. For example, tracing works very well in mountain environments where the conventional area/velocity method is inappropriate due to ice cover or irregular channels obstructed by boulders (Elrick and Lawson, 1969). Atkinson and Smith (1973) also had successful results in determining flow rates with lycopodium spores and fluorescent dye in a more recent study.

A study by Brown, Ford and Wigley (1969) shows that tracers can be used to determine the water budget of a karst system. The fraction of sinking water that rises at a spring can be calculated by knowing the quantity of dye that was injected and measuring its concentration at a spring. If input and output flow rates and percentage of dye recovered data are available, then the water budget of the system may be determined.

Tracing tests are also used to determine basin divides and catchment areas of springs in karst areas (Bidovec, 1965, White and Schmidt, 1966). Dyes show the direction of runoff. Chemical analysis of water samples may also be of assistance in establishing the origins and direction of flow of karst waters as well as providing indications about the type of strata the water travels through (Richardson, 1968). Pilgram (1966) used radioactive tracers in measurement of travel times of storm runoff in a small catchment. He was able to convert activity records at the basin's outlet into hydrograph data of the storm runoff. It was then possible to relate the discharge data to a particular instant and location of the basin. This method allows the identification of the contribution of different parts of the basin to the total flood hydrograph.

2.1.6 Additional Methods

There are several other methods of investigation of inaccessible cave systems in addition to tracing. One such method is microgravimetry or weighing the sub-surface. Recent publications (Arzi, 1977, Omnes, 1977) demonstrate this to be an effective and useful technique in the initial detection of cavities, especially when combined with exploratory drilling.

Resistivity measurement is a useful technique in finding air filled, or partially water filled, caves and delineating their outline (Manley and Garton, 1977). Some

methods are sensitive enough to respond to fractures and water filled cavities. This has an application in land use planning in karst areas (Kirk and Rauch, 1977). However, these methods are only capable of locating cavities to shallow depths (tens of meters), are time consuming, and there is controversy as to their precise interpretation. Resistivity surveys were attempted in Maligne Basin (Brown, 1972) with positive results which warranted drilling. The drilling was unsuccessful in locating a cavity.

Seismic techniques constitute a further method of initial investigation of inaccessible cave systems. Reflection seismology overcomes some of the problems of gravimetry and resistivity (Kirk and Snyder, 1977) and can locate cavities to great depths (500m). Recently developed compact equipment with simpler analytical techniques make it an attractive alternative for preliminary investigations. VIBROSEIS (a trademark of the Continental Oil Company) is a seismic technique which uses a continuous hammer source and continuous measurement to obtain the reflection and refraction patterns of waves on a grid of surface geophones. Barbier and Poleleau (1970) suggest a method of combining VIBROSEIS with optical filtering of the data, to produce a hologram (three dimentions) of the subsurface.

2.2 Tracer Tests of Medicine Lake: Early and Recent

2.2.1 Rhodamine WT

Rhodamine WT was chosen as the most ideal tracer type for the Maligne Basin. It is a Xanthene dye of the rhodamine sub-group and is a zwitterion but anionic (acid) in character. It is available from DuPont de Nemours & Co., who introduced it in 1964 (U.S. Patent 3367946 (1968))(Smart, 1972).

Lycopodium spores are not practical for the Maligne system. It is clogged at both the sinks and risings and this would filter spores. Large volumes of spores would be necessary and, large silt concentrations present in the water would clog the plankton nets while daily flood cycles could tear these recovery nets.

Tritium was rejected because of the required complex and expensive analysis procedure and equipment. Furthermore, it could be difficult to obtain permission for its use in a National Park.

Of the fluorescent dyes, Rhodamine B was rejected because of its carcinogenic properties. Fluorescein had been tried on the system with no results (Ford, 1968, Brown, 1972) while Rhodamine WT has been used in Maligne with good results (Brown, 1972). The relatively fast flow-through time of the system minimizes the possible photochemical decay dye loss in the Maligne River after resurgence but before samples are taken. Sorptive loss is minimized by storing the water samples for reanalysis after natural sedimentation has

taken place. For these reasons Rhodamine WT (in a 20% solution) was used for all the 1979 tests.

2.2.2 Early Tests-update

Table 4 summarizes the early tests on the Medicine Lake sinks. The first test was injected by D. C. Ford in 1966, sampled by E. Stone and the staff at the Jasper Fish Hatchery and analyzed by M.C. Brown. This test established the simple connection between the sink and springs. The 44-52 hour flow-through time (Ford, 1969, Brown, 1970, 1971, 1972) is now reduced by 24 hours due to a mistake in identification of the date of injection (M.C. Brown, pers. comm., 1979). The lake level of this first test was determined in October, 1979. A photo of that injection showed the lake height. The exact height was determined using an Abney level to sight on the recently installed lake level poles.

Tests 2-4 (Table 4) were completed by Brown and Ford. Test 2, using fluorescein, was unsuccessful, probably due to the fact that fluorescein decays quickly in sunlight and the lake was at a very high level ("nearly full") which would cause great dilution of the dye. Test 3 was a spring low level test (1425.3m) of the main sinks and established a 80 hour flow-through time. Test 4 was a late summer medium lake level test (1427.9m.) of the main sinks. Sampling began 44 hours after injection and indicated dye already present in the samples. Eye witnesses reported the river was pink the

TABLE 4

Summary of Early Dye Tests on Medicine Lake

	Date	Tracer Type	Tracer Quantity	Injection Site	Collection Sites	Collection Interval	Flow-Through Time	Percentage Recovery	Lake Stage (m.a.s.l.)
Test 1 Ford	June 26 1966	Rhodamine B	4.1 kg	main sinks small stream sink	Hatchery Pools Main Risings	12 hrs for 3 days 24 hrs for 37 days	44-52 hrs changed to 20-28 hrs	N.A.	1430.8
Test 2 Ford	Aug. 14 1967	Fluorescein	~11.4 kg	small stream sink	Main Risings Hatchery Pools Tea House Bridge	1 hr for 100 hrs 12 hrs for 7 days		N.A.	nearly full
Test 3 Brown	May 10 1968	Rhodamine WT 20%	1.8 kg	The Big Bend	Main Risings	1 hr for 150 hrs then irregularly	80 hrs	3%	1425.3
Test 4 Brown	Aug. 30 1970	Rhodamine WT raw wt.	5.4 kg	main sinks	Main Risings Hatchery Pools	44 hrs after injection	20 hrs		1427.8

N.A. - data not available

Source:Brown, 1972

previous afternoon and a 20 hour flow-through time was established. The interpretations of these tests will be discussed along with recent results in Chapter 4. For further information on methodology or analysis of the early tests see Brown (1972).

2.2.3 1979 Tests Methodology

INTRODUCTION

Tests 5-8 were completed by the author and M. C. Brown during the 1979 field season. The purpose was to test the two sets of sinks together and separately at different lake levels, to establish flow-through times and possible connections with the spring fed lakes located at the mouth of the basin. These springs were discovered by scuba divers in the late 1960's and brought to the attention of the author and M.C. Brown by J. Todgham, Senior Park Interpreter, who had thoroughly investigated these springs. Test 9 was completed by the author and J. Todgham with the purpose of establishing the possible connection of the small tributary streams which flow out of surface deposits into the Maligne Canyon gorge.

Sampling and Analysis

Water samples were taken from the Maligne River at the Warden Station (Figure 1). For Test 5 samples were hand collected approximately every three hours and analyzed on site so that the sampling interval could be increased when the dye was first detected. For Tests 6-8 a Borden Automatic

Liquid Sampler was used to take hourly samples from the river (see Appendix 2 for an explanation of the sampler).

The samples were analyzed on site, then stored in quartz glass sample jars which had been rinsed with distilled water in order to be reanalyzed at a later time. A Turner III Fluorometer was kept in continuous operation in the field. It was equipped with a primary sandwich filter of two Corning 5-46 (see Appendix 3). The secondary sandwich filter was composed of two Corning 590. The lamp used was the general purpose U-V lamp (G.E. F4T4/BL). Cuvettes used for samples were the Pyrex 12X72 mm culture tubes. These were rinsed and tested with distilled water before and after each sample. Appendix 3 explains the optical system of the fluorometer. Rhodamine WT is visible in concentrations of approximately $1:10^6$ and is detectable with the fluorometer at dilutions up to $1:2X10^9$.

Activated carbon detectors were placed at selected locations within the system (Table 5). The carbon was tied in nylon mesh bags and placed in the flowing water. Analysis of the detectors took place in the lab at the University of Alberta. If dye is present in the water the carbon surface will adsorb it. Elution in the lab with a solution of 10% ammonium hydroxide in 50% aqueous I-propanol will replace the adsorbed dye molecules with alcohol molecules. The released dye molecules will return to solution. The solution is then tested in the fluorometer.

Smart (1972) and Smart and Brown (1973) demonstrate

TABLE 5

Summary of 1979-1980 Dye Tests on Medicine Lake

	Date	Tracer Type	Tracer Quantity	Injection Site	Collection Sites (detectors)	Collection Interval	Flow-Through Time	Lake Stage
Test 5	May 14 1979 1600	Rhodamine WT 20%	~3 kg	side sinks	5 & 6 Bridges 3 Hatchery Pools	~3 hrs	>120 hrs	1426.7 m
Test 6	June 18 1979 2000	Rhodamine WT 20%	5 kg	main sinks	5 & 6 Bridges Main Risings Hatchery Pools Beauvert, Edith and Dead Man's Hole	1 hr	16 hrs	1428.8 m
Test 7	July 26 1979 1730 m 1930 s	Rhodamine WT 20%	11 kg m 11 kg s	main and side sinks	Main Risings Hatchery Pools Tributary Streams 3 lakes	1 hr	11-13 hrs	1436.9 m
Test 8	Oct. 5 1979 0900	Rhodamine WT 20%	16 kg	main sinks	Main Risings Hatchery Pools 3 lakes Tributary Streams	1 hr	41 hrs	1426.2 m
Test 9	March 15 1980 1300	Rhodamine WT 20%	5 kg	main sinks	Tributary Streams			ice-covered

through laboratory experiments how dye loading, initial solution concentration, and time since adsorption occurred, all influence maximum fluorescence upon elution. Greater dye loading on the carbon will lead to higher maximum fluorescence on elution. Furthermore, high initial dye concentrations are necessary in order to optimise carbon elution. These effects are due to the adsorption of more larger dye micelles at high concentrations than at low ones. Finally, desorption and redistribution of the dye occurs in open flow systems over time. Even in relatively clean waters, exposure for over one week will drastically reduce the amount of dye adsorbed.

For Tests 6-8 (Table 5), detectors were placed in the lake bottom springs; two sites in Lac Beauvert, one in Edith and one in Dead Man's Hole (one of the Twin Lakes) (Figure 1). The springs in Lac Beauvert are at a depth of 18m (60') below the surface and both the Edith and Dead Man's Hole springs are at a depth of 9m (30') . A styrofoam float was tied to a rock and the detector tied halfway up the string from float to rock (Figure 10). This apparatus was necessary in order to locate the detector for recovery, as the rock would sink into the lake bottom sediments. All underwater detectors were labelled with the date of placement and an explanation that its position was part of a research project so that other divers would not remove it. In addition slightly subsurface floats were placed above the spring locations so they could be easily located from a canoe.

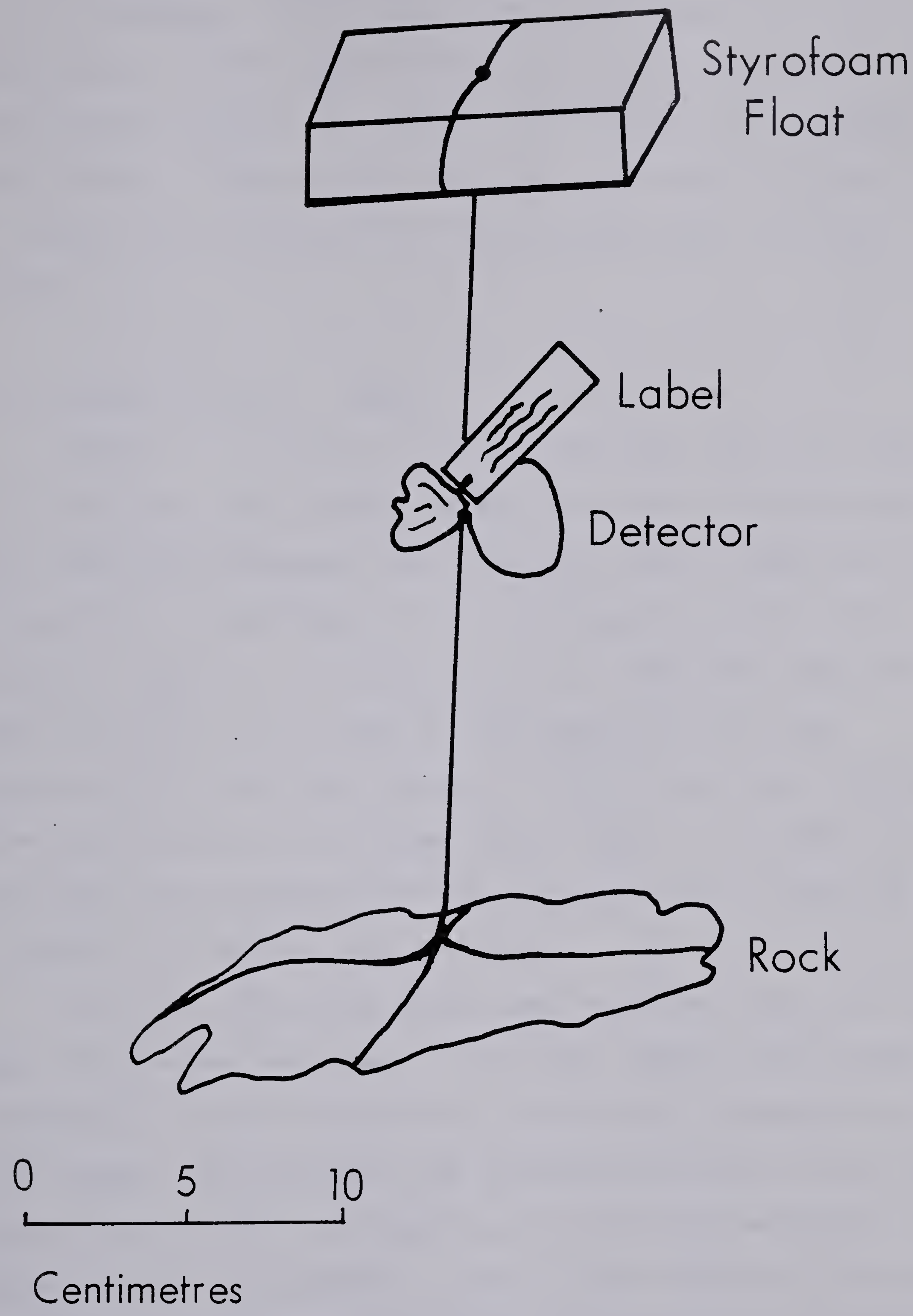


Figure 10
Lake bottom Detector

J. Todgham, Senior Park Interpreter, set up the procedures for the scuba diving volunteer programs. He also did the diving with assistance from Naturalist C. LaMarre and Warden J. Woodrow. For the July, 1979 test B. Glover and R. Wong of the University of Alberta assisted with the diving.

2.2.4 Test 5, May 14, 1979

Table 5 is a summary of the 1979-1980 tests. For the first of the recent tests, on May 14, 1979, at 1600 hours, 3 kg of dye were injected into the side sinks of Medicine Lake (Figure 11). (See Figure 7 for the location of the side sinks of Figure 11.) The lake was at a very low stage of 1426.7m (4679.5′). It had not yet begun to fill and consisted of a few small pools at the northern end. Maligne River was also at a low flow stage. Table 6 is a chart of the mean daily discharge of the Maligne River on the day of injection for each of the 1979 tests.

For Test 5 discrete water sampling took place for five days. No dye was detected in the water samples even after reanalysis in the lab to allow for natural sedimentation. The longest flow-through time measured previous to this test was 80 hours (1968) so sampling was discontinued after 120 hours. No dye was present in any carbon detectors that were in place for the first five days after injection. However, all the detectors placed in May 19 (5 days after injection) and removed May 28 (14 days after injection) were positive.

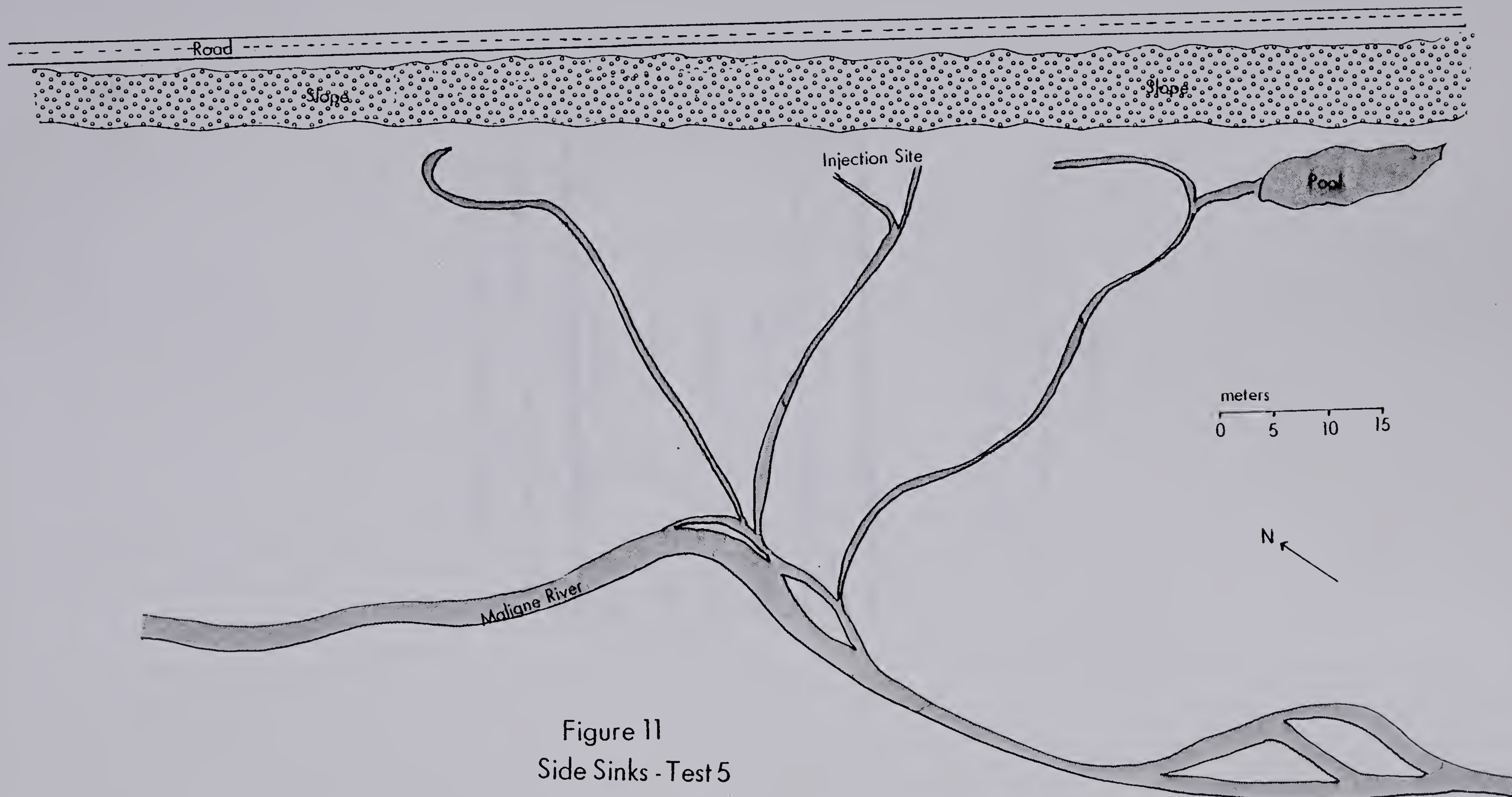


Figure 11
Side Sinks - Test 5

(see Figure 7 for location of side sinks)

TABLE 6

Discharge of the Maligne River

during the 1979 Dye Tests

Test #	Date	Q (cms)
5	May 14	4.36
6	June 18	39.20
7	July 26	41.30
8	October 5	11.80

Guage located at the Warden Station

Source:Water Survey of Canada

A. Young, who was scuba diving in Lac Beauvert May 28, 14 days after injection, reported seeing a pinkish tint to the water above the springs at the lake's bottom (J. Todgham, pers. comm., 1979). Unfortunately no water sample was taken of this "dye cloud".

INTERPRETATION

This test of the side sinks established the longest flow-through time of the system to date. At a low lake level of 1426m, the dye took a minimum of 120 hours to appear. The side sinks are located approximately 2km (1.6 mi) up Medicine Lake from the main sinks and this fact alone would contribute to a longer flow-through time in comparison to the 1968 test of the main sinks at a similar lake level.

This test reveals information that updates the model of the system proposed by Brown (1972). He postulated that the cave was a series of channels of varying elevations. The connection was relatively fixed between the main sinks of Medicine Lake and the lower Hatchery Pools. Furthermore, the inputs between Medicine Lake and the Main Risings flowed to the higher (in elevation) Main Risings along the Maligne River (Figure 12). This was based on the large dye loss of the tests. The May, 1979 test shows the side sinks to have good connections with both sets of risings. The system must have mixing at all lake levels, not just high lake levels. These channels may have tributaries as well as distributaries (see Test 8). As well, the mixing may occur by the coming together of vertically separate channels as

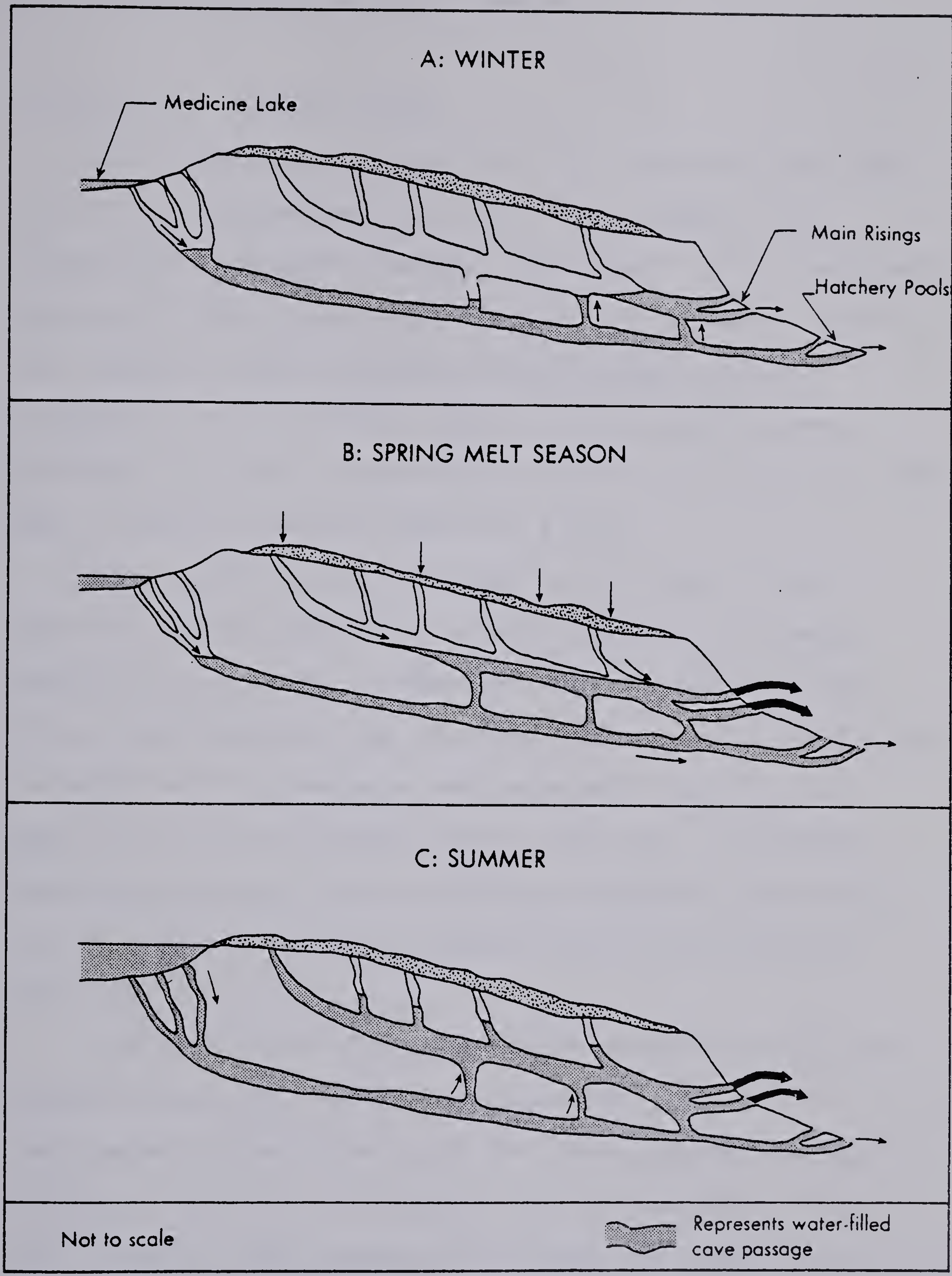


Figure 12
1972 Model of Maligne Cave
Source: Brown, 1972

well as horizontally separate channels.

2.2.5 Test 6, June 18, 1979

Test 6 was begun on June 18, 1979. Medicine Lake had risen to an intermediate level of 1428m (4686.5′) an increase of 2.1m above the May, 1979 level. All risings were flowing. At 2000 hours, June 18, 5 kg of dye were injected into the main sinks. Expected flow-through time was estimated to be no shorter than 24 hours based on the previous tests and considering the still relatively low lake level. Table 5 lists the detector sites.

Water sampling was continued for 182 hours after injection and no dye was detected in the field. However, reanalysis in the lab in Edmonton showed a positive test. Natural sedimentation had occurred in the sample bottles and low magnitude fluorescence was detected. Figure 13 is a graph of the flow-through time of this test. Fluorometer readings were converted to true dye concentrations using freshly prepared standards and the calibration curve of Figure 14.

This test is considered positive despite the low dye concentrations for the following reasons. The time-concentration curve is of the form expected for karst investigations. This is a quick rise followed by a long tail. As well, the concentrations begin at 0 and return to 0 after the dye has passed.

Figure 13 shows that the dye arrived 16 hours after

Figure 13

Test 6 Flow-Though Time

injection June 18, 2000 hours

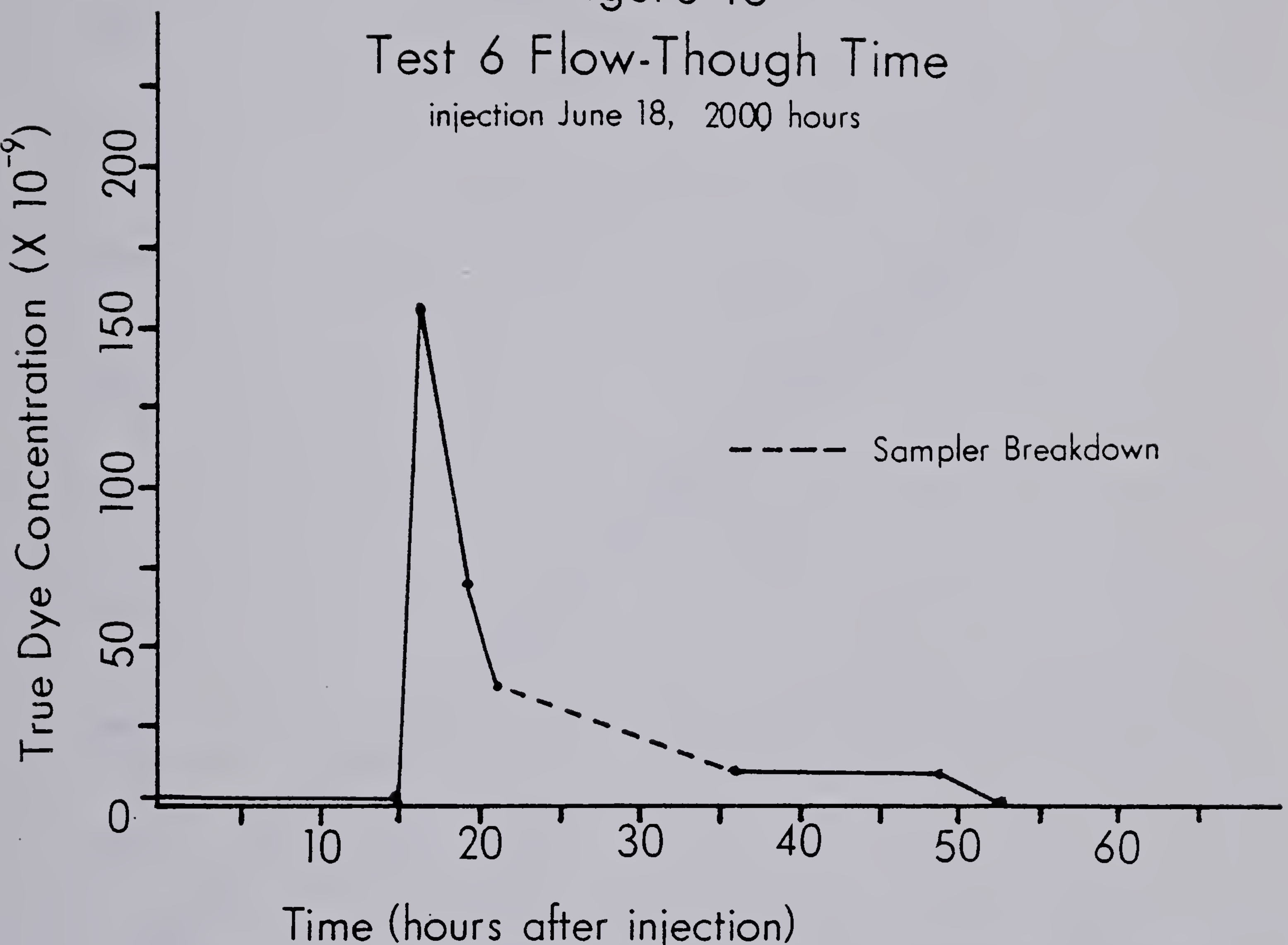
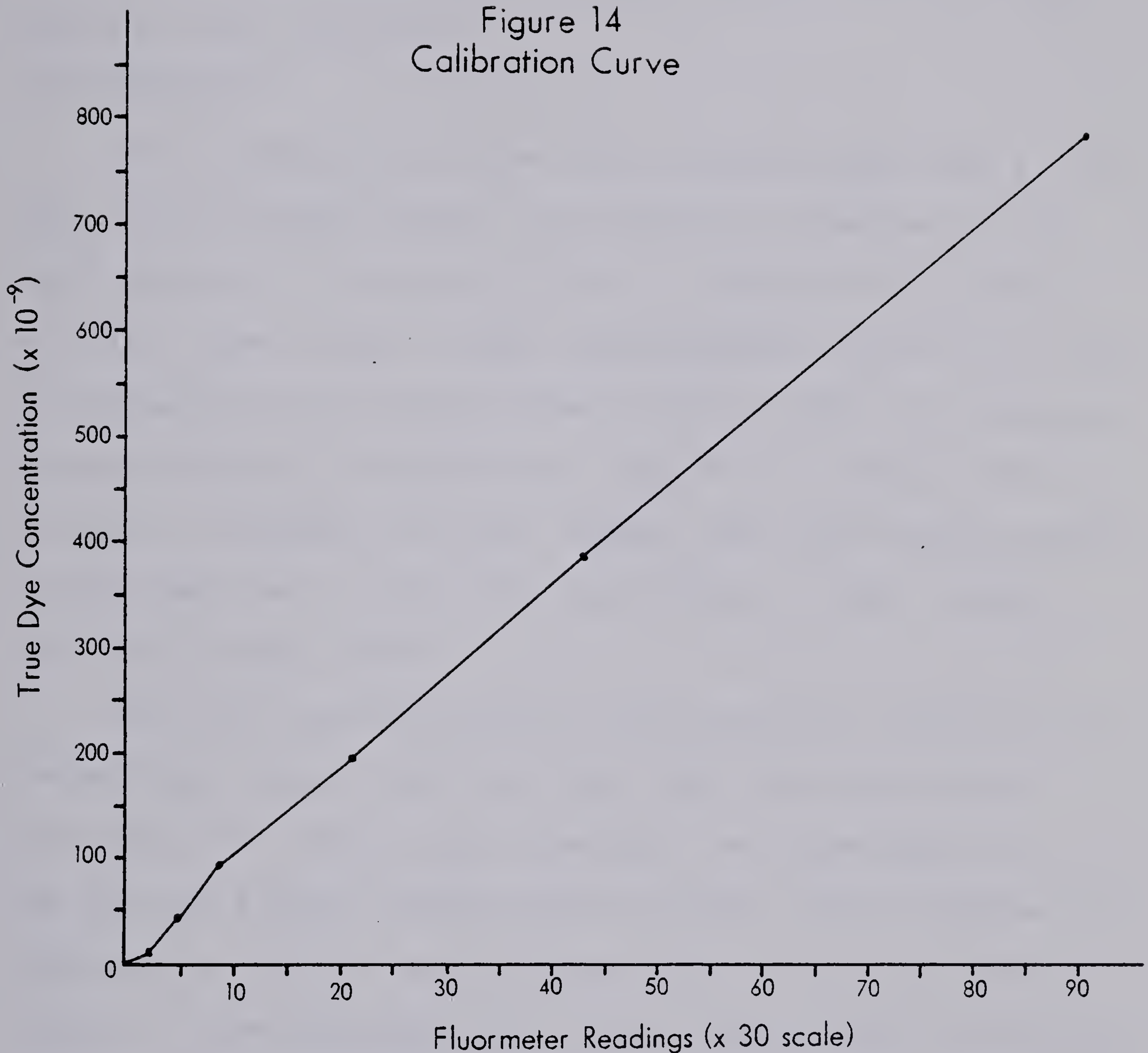


Figure 14
Calibration Curve



injection and was detectable for another 36 hours. Fourteen hours of the curve had to be estimated due to sampler breakdown. The flow-through time for this lake level was grossly over-estimated so the detectors were put in place during the final portion of the dye's appearance. All the detectors were negative.

INTERPRETATION

Test 6 demonstrates that the Maligne system has a very fast flow-through time for its distance, relative to many karst systems of the world. This is indicative of a very efficient cave. Brown (1966) investigated a system of 19.3km (12 miles) with a vertical drop of 381m (1250') in Jamaica and established a flow-through time of 14-17 days. Here in Maligne, a system of similar length, the flow-through time can be less than 1 day. (See also Bidovec, 1965, Trombe, 1952, and Burden, 1963.)

This test demonstrates the large amount of dye loss in the Maligne system. Only low magnitude fluorescence was detected with 5 kg of dye injected. The large majority of the dye was either finding other outlets, being adsorbed on sediments or diluted beyond detection. It is quite likely that all three processes are active. Dye was only detectable after natural sedimentation had occurred in the sample jars. Test 8 (see below) adds one new output to the system, the Lac Beauvert springs. In addition, the large amounts of water present in the system at high flow will certainly dilute the dye to low concentrations.

2.2.6 Test 7, July 29, 1979

Test 7 was an attempt to test both sets of sinks of Medicine Lake simultaneously to have resulting double peaks on the time concentration curve. Even though the side sinks sink directly into bedrock and the main sinks sink through the landslide debris, it was expected that the side sinks would have a longer flow-through time than the main sinks. This was based on the 80 hour flow-through time of the 1968 test of the main sinks compared to the 120+ flow-through time of the May, 1979 test of the side sinks at a similar lake level. The lake level for Test 7 had risen to just over the half full mark, 1436.9m (4713.2′), which was the highest level it reached during the 1979 tests.

At 1730 hours, July 29, 11 kg of dye were injected into the main sinks and at 1930 a similar amount was injected into the side sinks in an underwater injection (Table 5) (see Appendix 4 for an explanation of the underwater injection procedures).

For Test 7 water samples were not analyzed in the field because of fluorometer breakdown. Sampling was continued for 6 days after injection and all detectors were changed every 2 days, twice after the initial placement.

Figure 15 shows the flow-through time for Test 7. The dye arrived 11 hours after injection and was detectable for an additional 15 hours. Unfortunately the anticipated double peak is not evident on this graph.

Analysis of the charcoal detectors confirms this to be

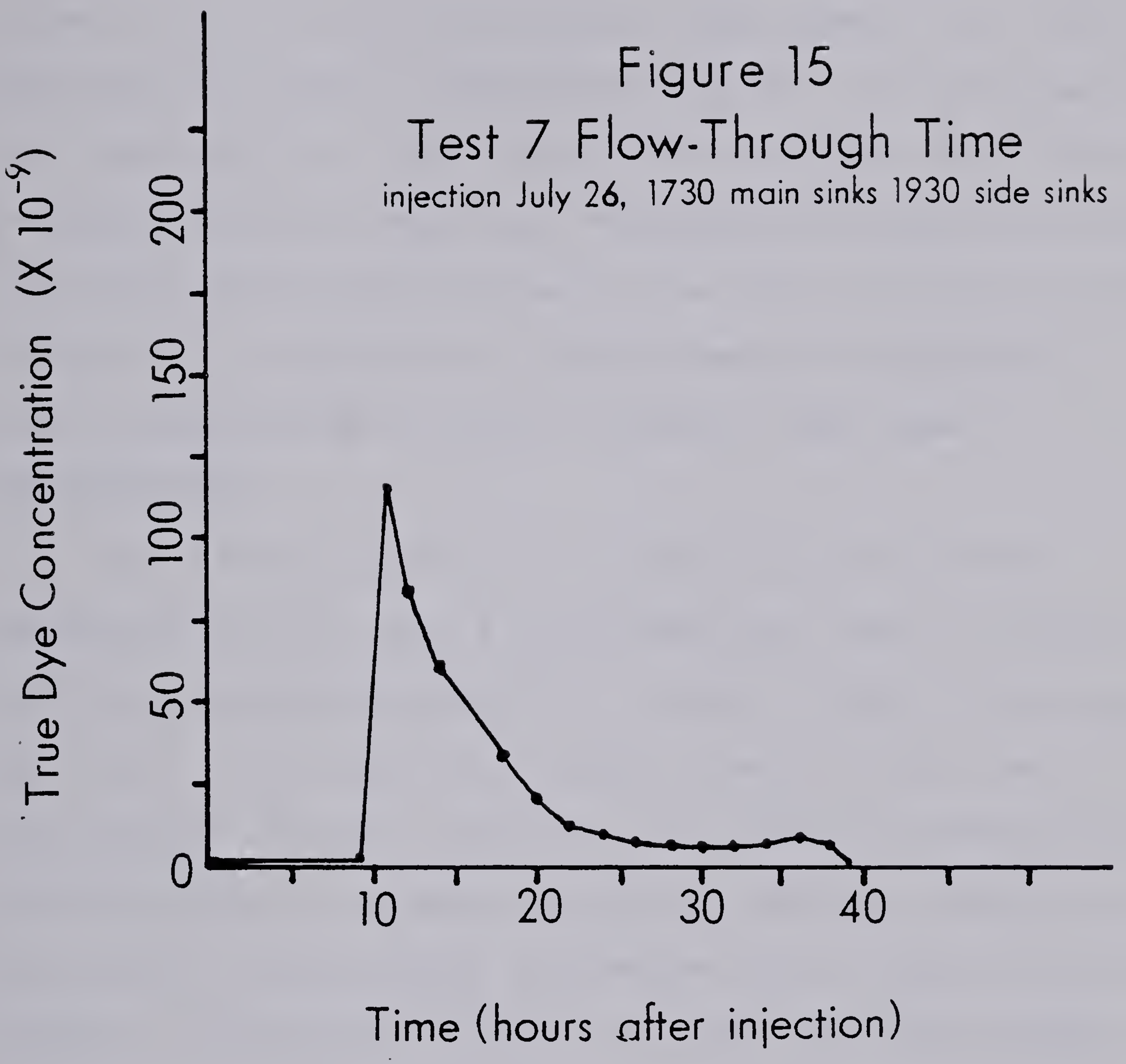


Figure 15
Test 7 Flow-Through Time
injection July 26, 1730 main sinks 1930 side sinks

the fastest flow-through time measured for the system to date. The detectors in place the first two days after injection in the springs along the Maligne River, 5th and 6th Bridges and the Hatchery Pools had very positive values(3X scale of 40 for example)(see appendix 3). The detectors in place in these locations the following two days were less positive (30X scale of 40) and from that time on the detectors were negative. The detectors from the spring fed lakes and the ones placed in the small tributary streams showed very low amounts of fluorescence, not enough to confirm these as part of the system at that time.

INTERPRETATION

Test 7 was significant in that it was the first successful test at such a high lake level when dilution of the tracer beyond detectability is very likely. Even more important is the fast flow-through time for this test. Flow-through time for the over-spill water following the surface channel from Medicine Lake to Maligne Canyon was determined to be 6 hours, 45 minutes (Ford, 1979). The cave system is constricted at both its sinks and the risings yet the flow-through time at high lake level appears to be approximately four hours longer than surface flow. Again, this suggests a very efficient and well developed cave.

2.2.7 Test 8, October 5, 1979

Another low level test was completed in October, 1979. Medicine Lake had almost disappeared, being at a level of

1426.2m (4678'). This was 0.5m lower than the May, 1979 test of the side sinks. At 0900 hours, 16 kg of dye were injected into the main sinks. Sampling continued for 6 days after injection with no dye detected in the field. The detectors were changed every two days at all locations except for those in the spring fed lakes.

Figure 16 shows the time concentration curve for Test 8 after reanalysis in the lab. The dye arrived 35 hours after injection and was detectable for another 60 hours. Analysis of the detectors at 5th and 6th Bridges and those of the Hatchery Pools confirmed the results of the water samples. Again, the detectors in the tributary streams on the south wall of Maligne Canyon were marginally positive. The detectors in Lake Edith and Dead Man's Hole were negative. However, the detectors in Lac Beauvert, in two locations, were positive. These detectors were removed 14 days after injection.

INTERPRETATION

This test was significant because it established an additional output to the system. Ford (1969, p.14,17) had hinted at this possibility in one of the Parks Reports writing,

> "all sink in the bottom of the (Medicine) Lake and move as proper karst flow to springs in lower Maligne Canyon or adjacent points along the margin of the Athabasca River floodplain. .....the dispersion of springs over a wide frontage and the

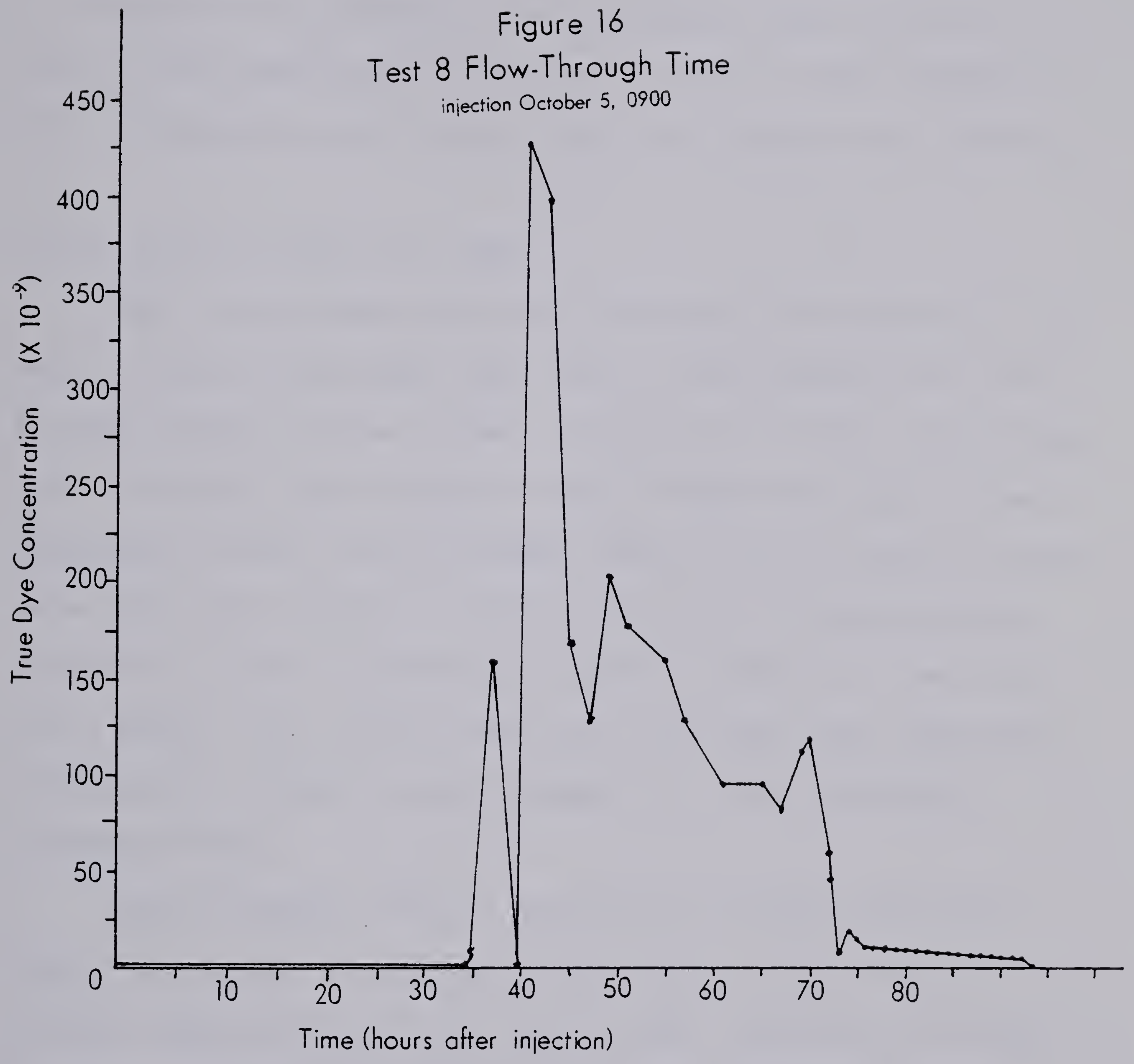


Figure 16
Test 8 Flow-Through Time
injection October 5, 0900
True Dye Concentration (X 10⁻⁹)
450
400
350
300
250
200
150
100
50
0
10
20
30
40
50
60
70
80
Time (hours after injection)

> limited hydrostatic head suggest an exit buried at some depth by the Athabasca River gravels. This is now discharging upward through an initial fissure system that has been substantially shortened by the independent erosion of Maligne Canyon down into it."

Test 8 confirms that the cave water flows to the Athabasca River floodplain and into at least Lac Beauvert as springs.

2.2.8 Test 9, March 15, 1980

Test 9 was completed with the intent of connecting the small tributary streams that flow off the valley side into Maligne Canyon to the system. On March 15, 1980, 5 kg of dye were injected into the main sinks of Medicine Lake. It was necessary to cut a hole through 76cm of ice to reach flowing water for this injection. Detectors were in place before injection in four locations (Figure 5)(Table 5), and left for 1 month. Only two of the four detectors were recovered and analysis showed no dye present in these detectors.

INTERPRETATION

These streams flow all seasons of the year and the water remains at a constant temperature. They flow out of surface deposits but it is likely that the contact between Palliser limestone and Banff shale is underneath these deposits at the start of these small streams. For these reasons it was suggested that these streams represent minor springs issuing from the cave. The negative results may indicate one of three things. These streams may be wholly

fed by surface runoff and do not represent water from the cave. These streams may be springs from the cave but the dye was diluted beyond detection. Finally, these streams may be cave streams but the dye was desorbed from the detectors in the time left in place. Further investigation of these streams is recommended.

3. CHAPTER THREE, HYDROGRAPH ANALYSIS OF THE MALIGNE RIVER

3.1 General Review of Hydrograph Analysis

Analysis of a stream's hydrographs has proven to be an effective tool in the investigation of its drainage basin. Most of the techniques of analysis have been applied to storm hydrographs but these may be expanded for use on yearly hydrographs. The hydrograph will reflect characteristics such as size, shape, and slope of the basin from which the water drains. Geology, and soil types, vegetation (Figure 17) and possible glacial cover, all influence the shape of a hydrograph. For example, the rising limb of a hydrograph is generally concave upward and it partly reflects the infiltration capacity of soils in the basin. A sudden steeply rising limb on a hydrograph reflects immediate surface runoff and little absorption. If the basin has a large storage capacity and absorptive surface, the hydrograph will reflect this with a lower peak compared to a hydrograph of a basin with little storage capacity. The recession curve represents outflow from basin storage. Its slope will largely reflect the physical characteristics of the basin related to storage properties (Morisawa, 1968).

The shape of a hydrograph reflects watershed characteristics as well as the time and space distribution of precipitation or melt inputs. Detail on the precise shape and recession curve form can be described by several indices (Figure 18)(Gregory and Walling, 1973). *Lag time* is the

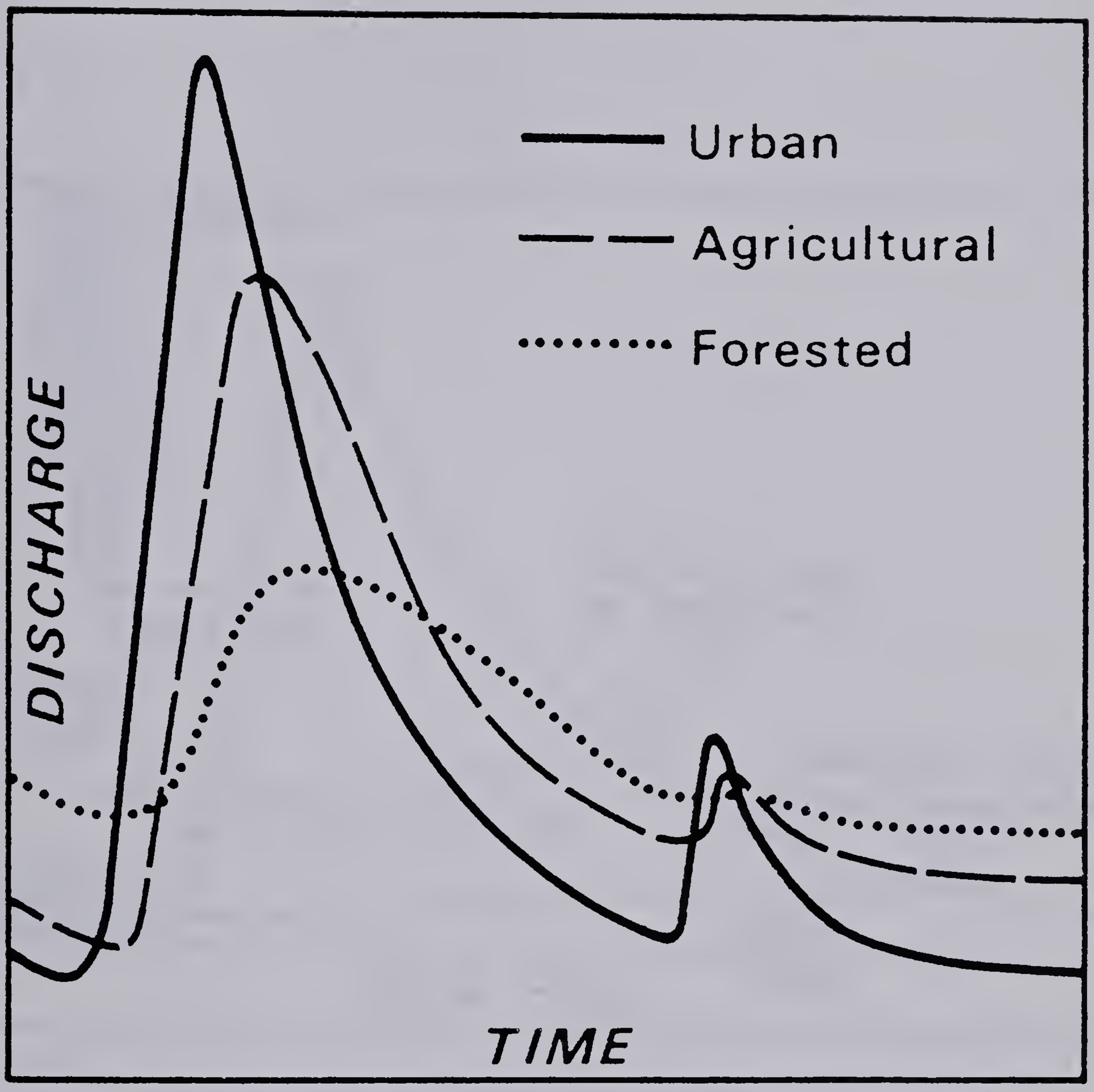


Figure 17

Land Use Cover Hydrographs

Source: Gregory and Walling, 1973

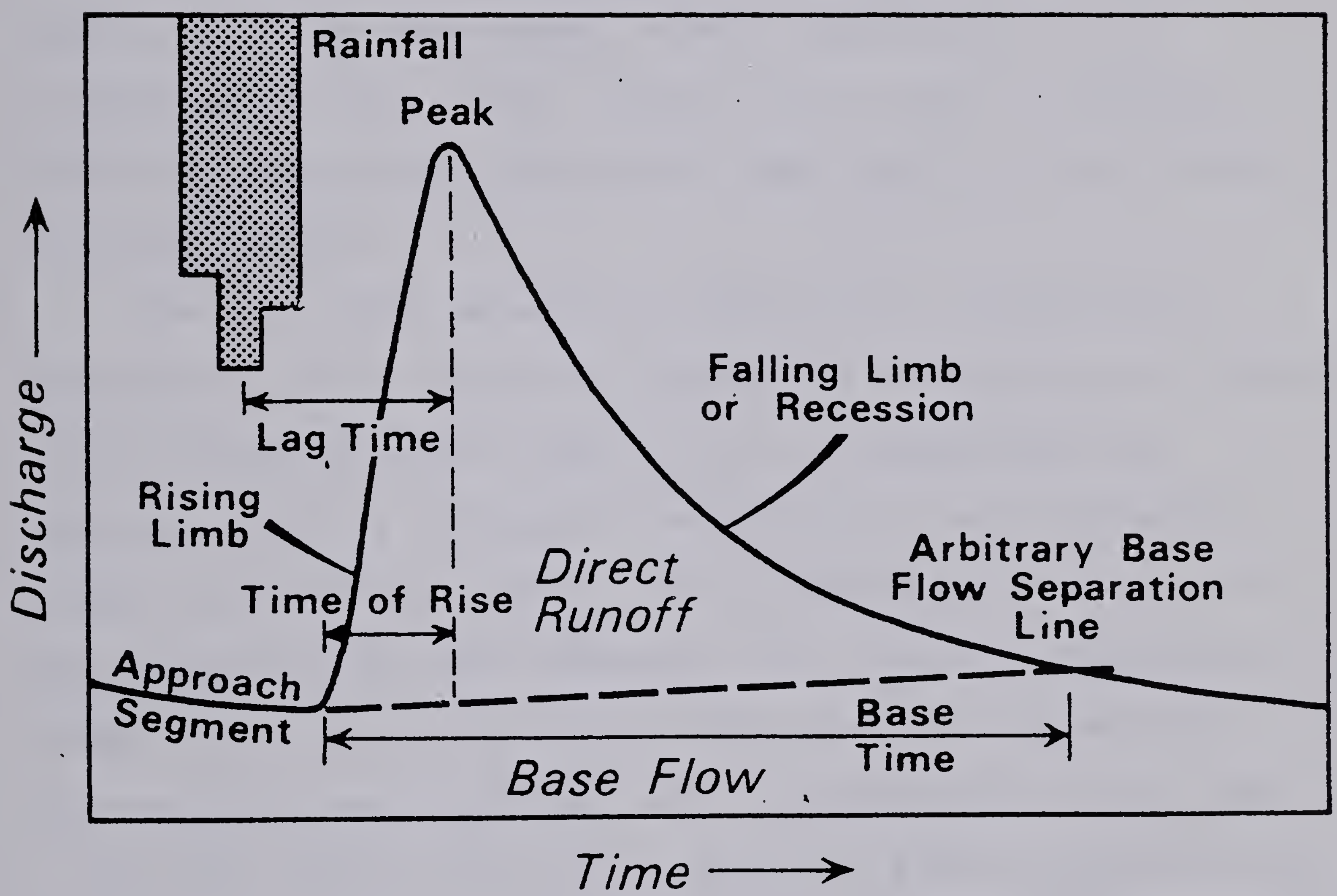


Figure 18

Characteristics of a Storm Hydrograph

Source: Gregory and Walling, 1973

interval between the center of gravity of the graph of effective input and the hydrograph peak. *Time of rise* is the interval between the beginning of the rise and the associated hydrograph peak. *Base time* is the basal width of the hydrograph and depends on the technique employed. *Peak to mean ratio* is a measure of the hydrograph peakedness where the mean is the average length of storm runoff for the base time of the hydrograph. *Runoff percentage* is the proportion of the rainfall occurring as runoff. *Effective Rainfall* is the depth of rainfall equivalent to the volume of storm runoff.

Sherman (1932) presented a method of standardizing hydrograph form in order to isolate the characteristic shape of the catchment under study. This is accomplished by applying the Unit Hydrograph concept which was updated by Gregory and Walling (1973). A Unit Hydrograph of duration T, was originally defined (Sherman, 1932) as the hydrograph of direct runoff resulting from 1 cm of rainfall generated uniformly in space and time over the watershed in unit time T. Gregory and Walling (1973) update this definition so that the term unit applies to rainfall amount (1 cm) rather than rainfall duration. As a result T may be varied to fit the study (Figure 19).

Relief undoubtedly influences runoff in a basin. This influence is based on the fact that steeper slopes provide more available energy than less steep slopes. The time of hydrograph rise and lag time will be shorter and peak

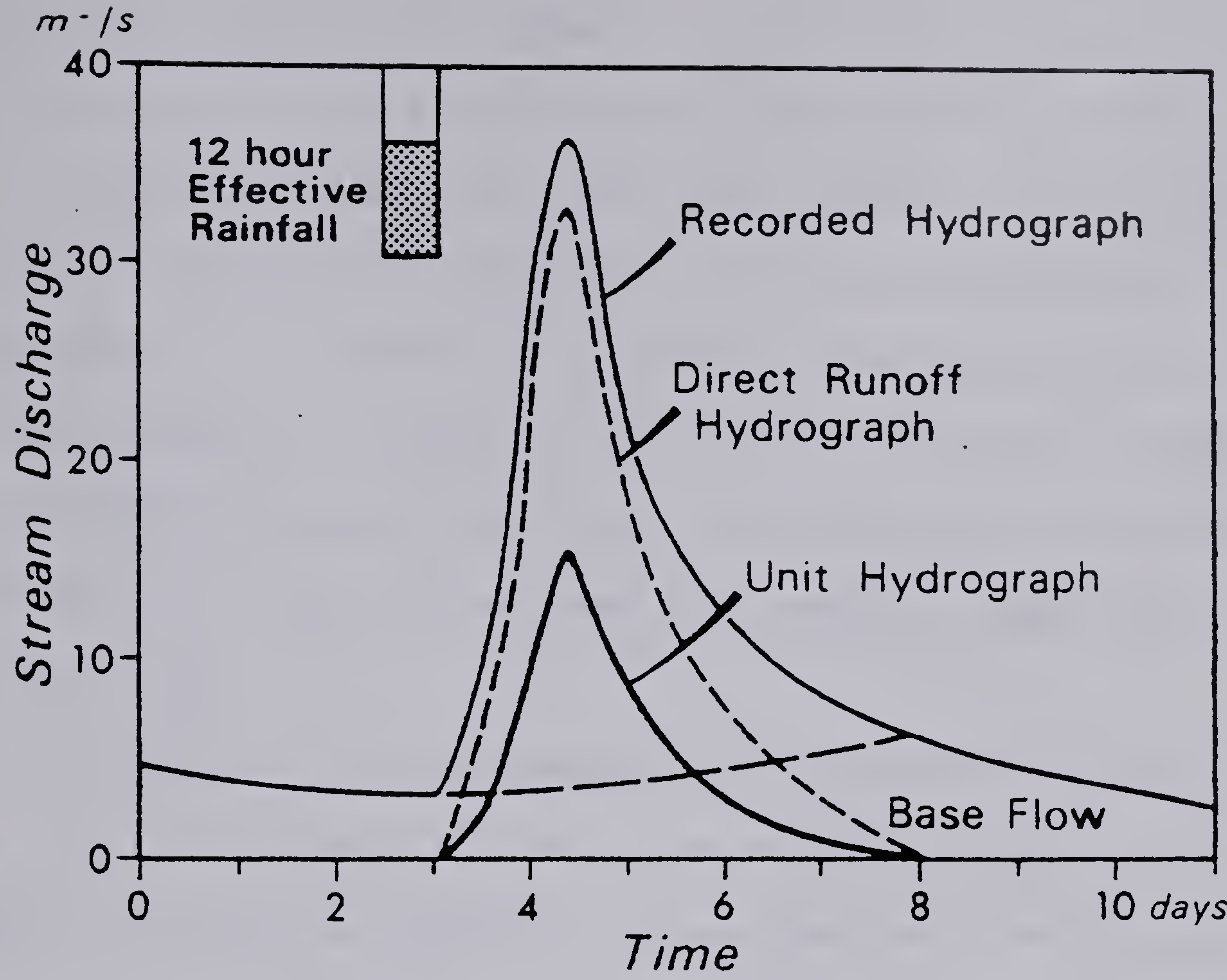
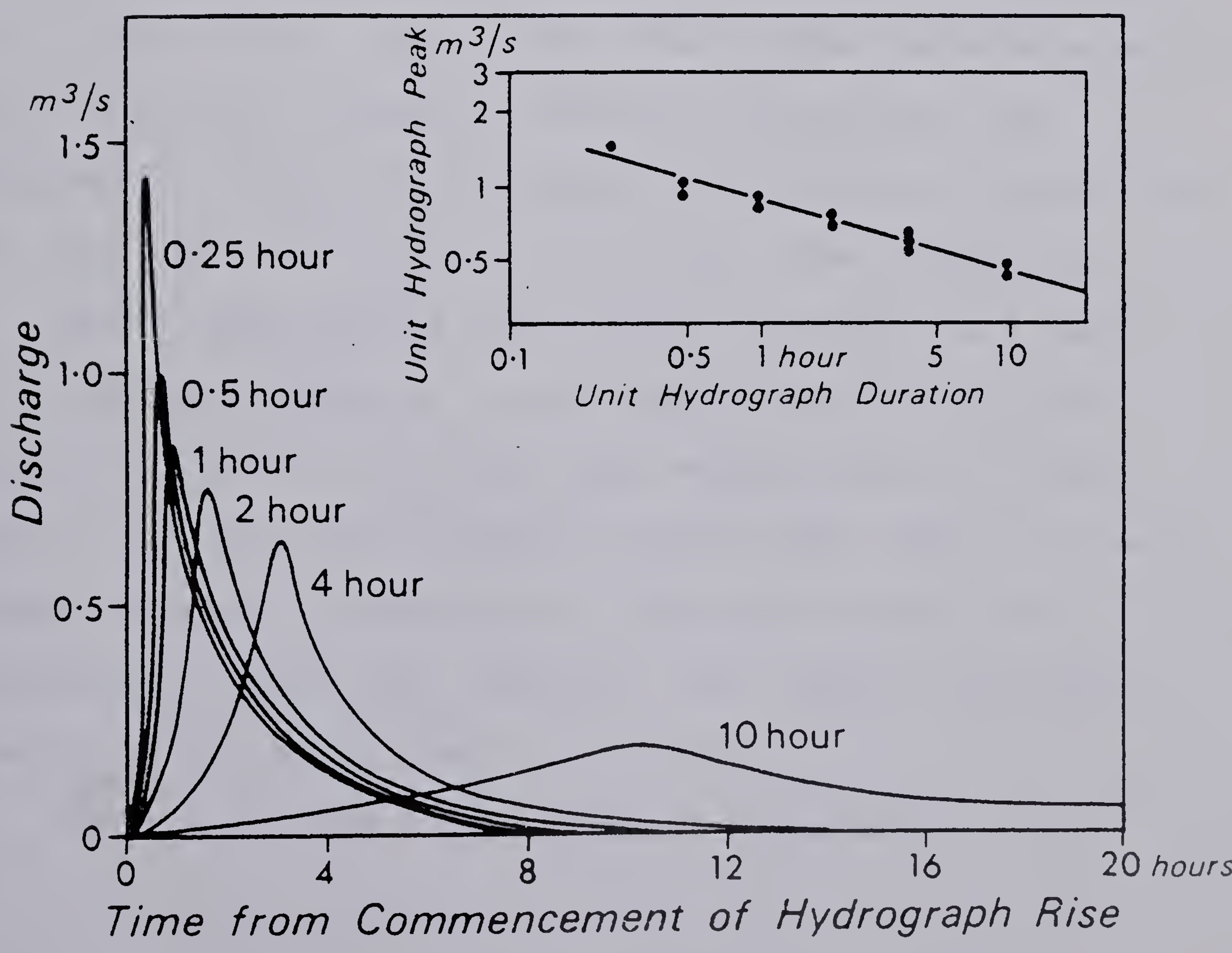


Figure 19

Unit Hydrographs Source: Gregory and Walling, 1973



discharge rate may be higher in the basins with the highest relief ratio (Figure 20)(Gregory and Walling, 1973).

Hypsometric analysis has been applied in the study of relief. The percent hypsometric curve was developed by Langbein et al.,(1947) as a method of expressing the area/altitude distribution of a basin. Strahler (1952) explained the procedures for calculating the dimensionless parameters so that curves may be compared regardless of the basins' scale.

Two ratios are necessary for construction of the curve. The first is a ratio of relative height or the ratio of height of selected contours above the basin mouth elevation to the maximum height of the basin. The second ratio is of relative area and is the ratio of area between the contours selected and the upper perimeter of the basin to the total basin area (Rains, 1969 p. 88). The ratios range between 0.0 and 1.0 and are plotted to construct the curve. The Hypsometric Integral may then be calculated as the ratio of the area under the curve to the total area (Figure 21).

Basin shape partly determines lag time, the time of rise and peak height on a hydrograph (Figure 22). Basin shape is related to the drainage network pattern. Where there is an efficient network (Figure 22e) there will be a slower rise but a higher peak. Where the network is lengthened (Figure 22d) there will be a quick rise but a lower and less sharp peak.

There have been numerous measures of basin shape

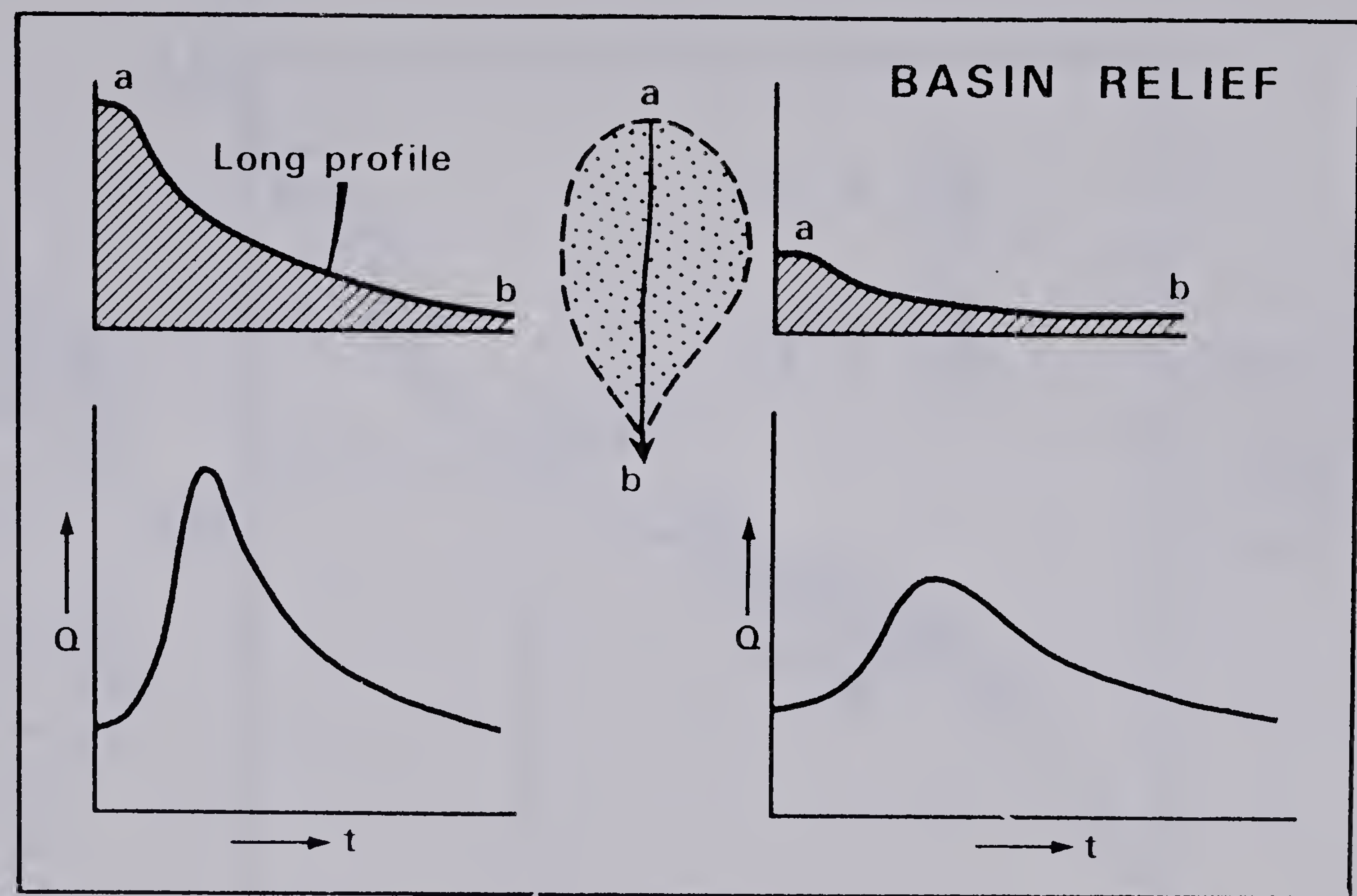


Figure 20

Influence of Basin Relief on a Hydrograph

Source: Gregory and Walling, 1973

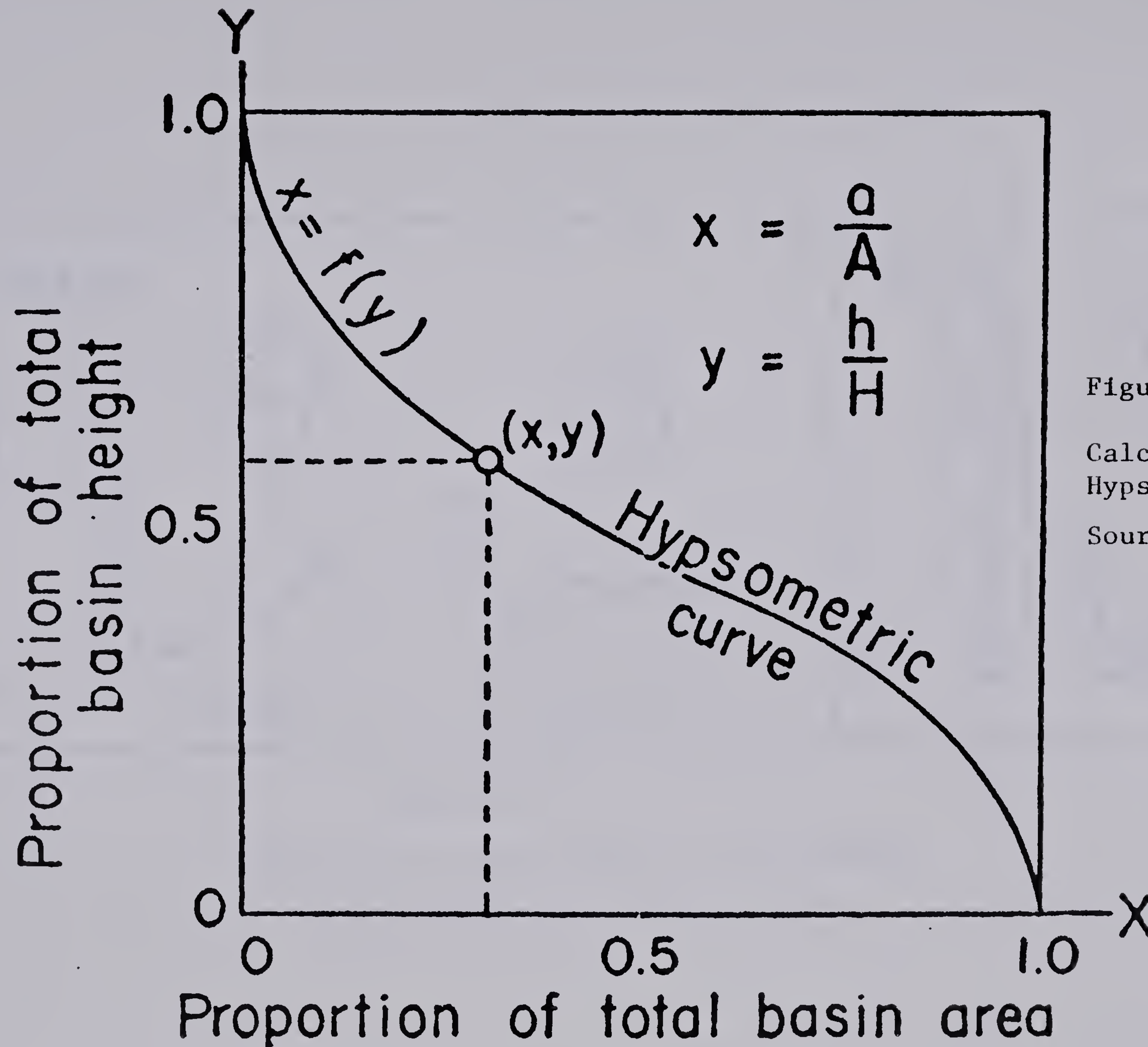


Figure 21

Calculation of a Hypsometric Curve

Source: Strahler, 1952

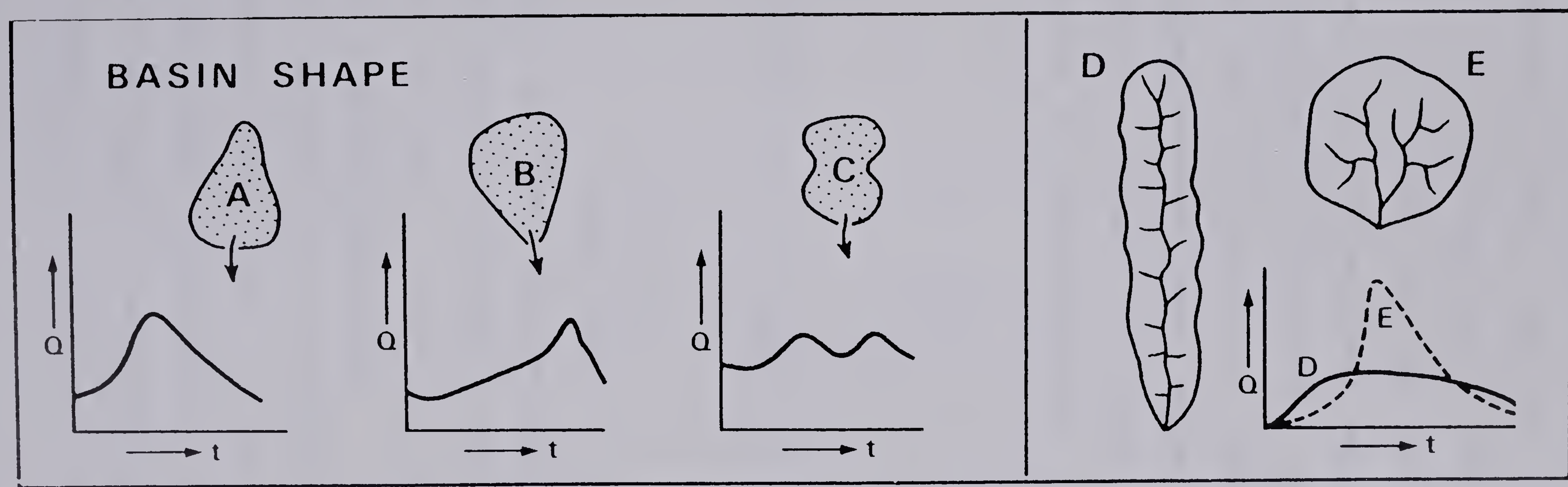


Figure 22

Influence of Basin Shape on a Hydrograph

Source: Gregory and Walling, 1973

presented in the literature. The early measures used the circle as a standard for basin shape (Miller, 1953, Maxwell, 1961). Chorley, Malm, and Pogorzelski (1957) proposed that few basins are of a circular form and a better standard of "ideal shape" would be the lemniscate loop (Figure 23). They presented two measures of shape based on the lemniscate loop. The first value is k, and is an indication of the relationship between maximum length and maximum width of the basin. When k=Unity, the basin is circular. K may be calculated with the following equation:

$$K = \frac{L^2\pi}{4A}$$

L=max length of basin from the mouth to some point on the divide.

π =3.1416

A=Basin Area

The second measure of shape presented gives an indication of how closely the actual drainage basin shape approaches the ideal lemniscate loop and is called the Lemniscate Ratio. Its calculation is quite complicated.

Hydrograph analysis is not at present a widely used tool in the investigation of karst systems. Aley (1963) suggests four basic model hydrographs for subsurface flow. Figure 24 shows highly generalized hydrographs for four such flow regimes. Hydrograph (a) indicates a free flowing cave

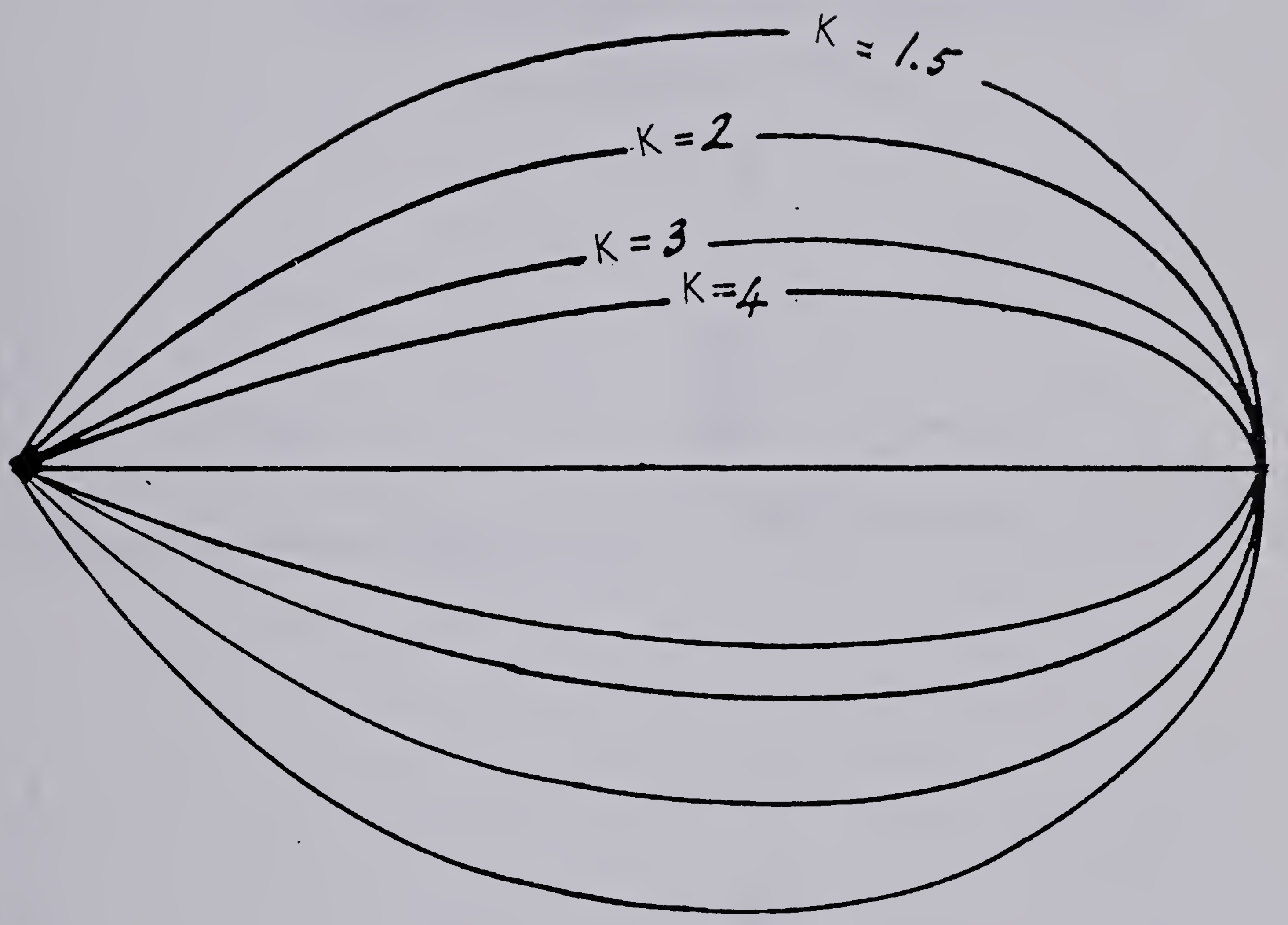
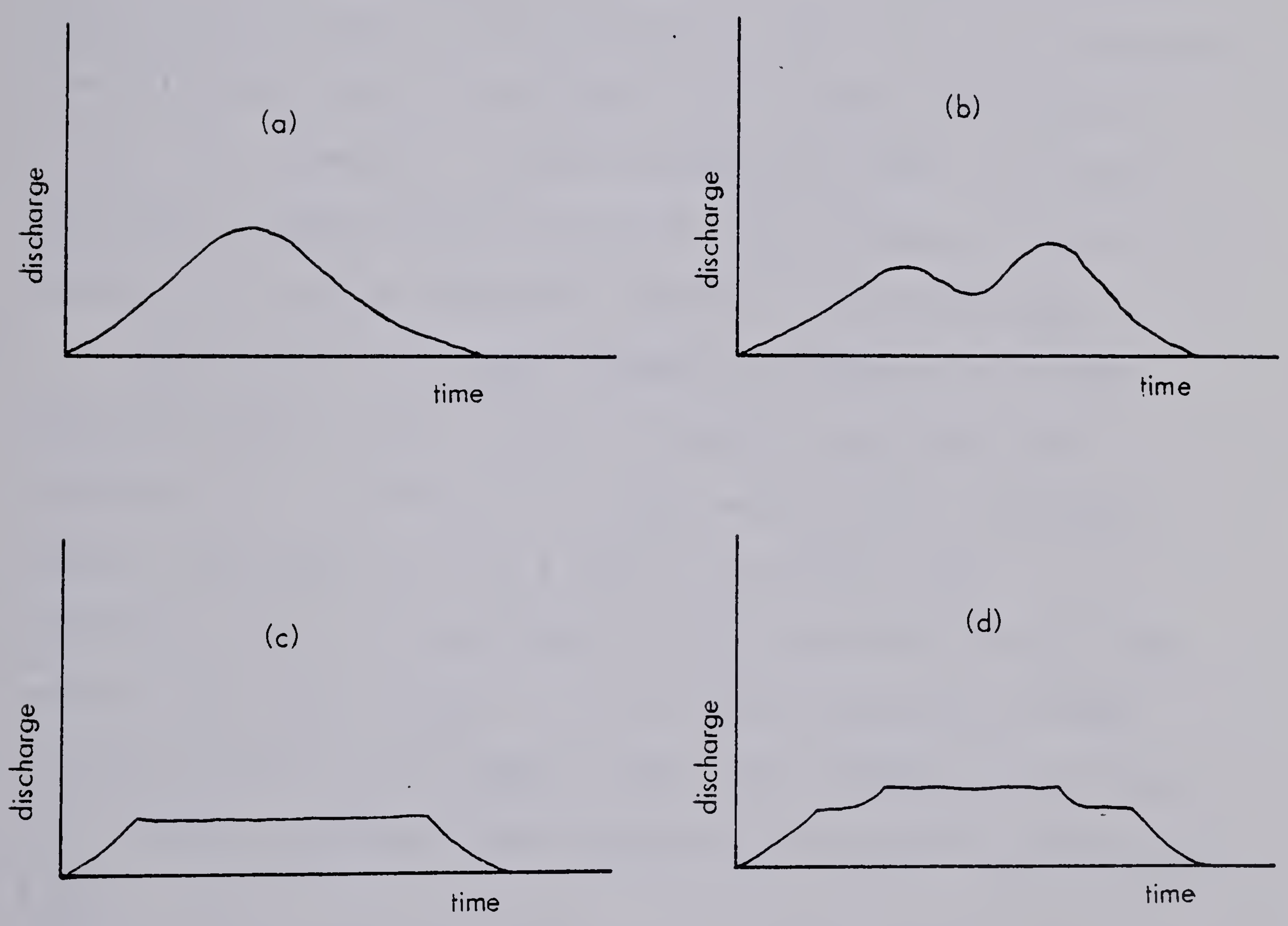


Figure 23

Lemniscate Loops

Source: Chorley, Malm, and Pogorzelski, 1957

Figure 24
Model Hydrographs for Subsurface Flow
in Limestone Terrain



Source: Aley, 1963

stream not delayed or impeded and is typical of a mature karst area. Often the tail will be greatly elongated by a carry-over from previous storms. Hydrograph (b) is an example of a free flowing cave stream with a delayed yield suggestive of the joining of two streams, each with different peaks. This is caused by the arrival of a volume of water that was delayed or perhaps traveled a greater distance than the water creating the first peak. A single stream fed by water with a long and short lag time between precipitation and arrival would also cause this shape of curve. For example, if a watershed had a portion covered with bare limestone while another portion had a glacial till mantle, this curve would be typical of its discharge.

Hydrograph (c) shows impeded flow where the volume carrying capacity of the underground stream has been reached. It is typical of springs which drain inundated caves. Hydrograph (d) is a special case of type (c). A reservoir may exist upstream of the constriction and the water rises high enough to find another opening through which to drain. This higher level cave inundation produces the secondary plateau superimposed on the primary plateau of Figure 24(c).

These four hydrograph models may be used to predict the rate and duration of flow. A unit hydrograph may be constructed and adjusted to the calculated storm value of subsurface flow. Duration of flow and flow volume at a given time may then be taken directly from the adjusted storm

hydrograph (Aley, 1963).

3.2 Maligne Hydrology

The Maligne River rises in the Brazeau icefield at an elevation of 2591 m.a.s.l. (8500'). It travels a total of 67.6Km (42 mi) to join the Athabasca River. The mean gradient is 23m km^{-1} (116.6 ft/mi). The steepest gradient is near the mouth of the river in Maligne Canyon. As the Maligne River cuts into the hanging portion of the basin above the Athabasca Valley, it drops 150m km^{-1}. Table 7 presents a comparison of selected data characterizing the Maligne and Miette River Basins (see Figure 25).

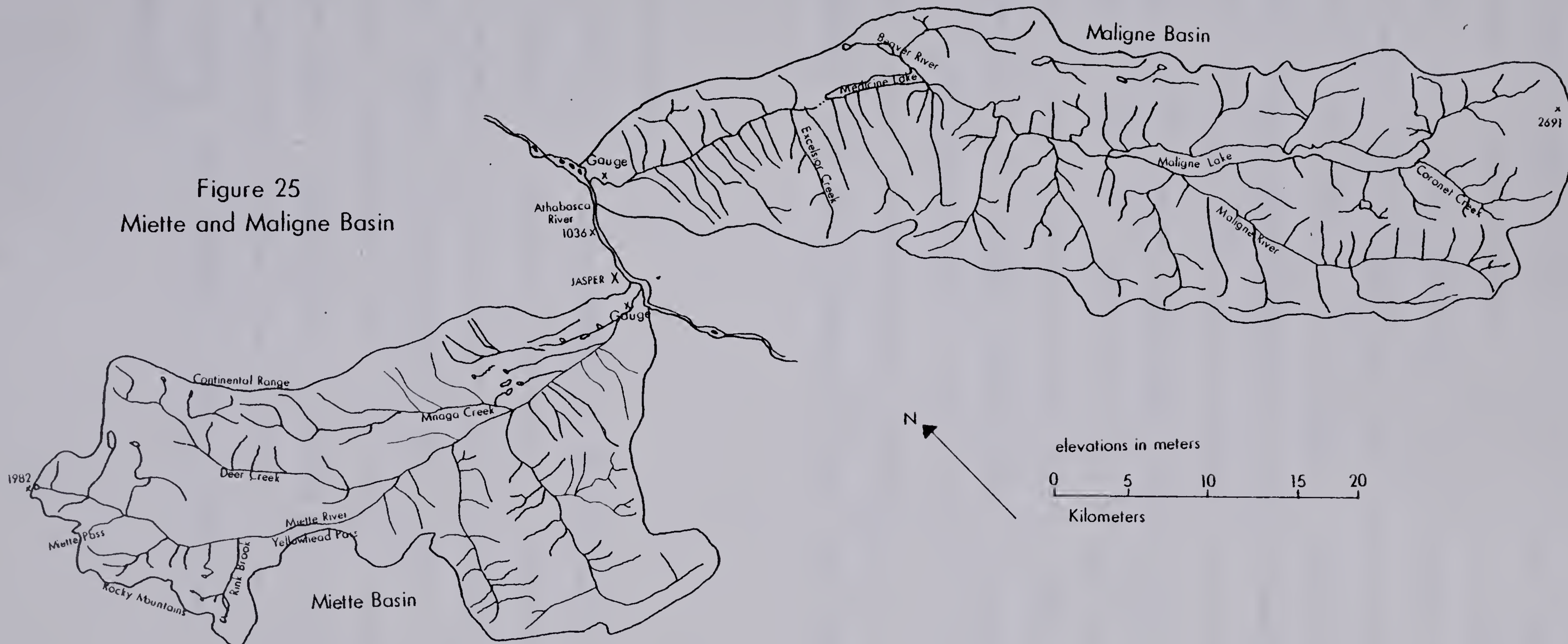
The Maligne River drains an area of 880km² (332 mi²) and has 5 major tributaries. These are Excelsior Creek, Beaver River, Coronet Creek, and two unnamed creeks that enter on the south side of Maligne River between Medicine and Maligne Lakes. The Maligne Basin is long and narrow, being 65km long and 20km wide (Figure 25). This shape should contribute to relatively lower peaks on the runoff hydrograph. In addition, the Maligne River flows into and out of two lakes, Medicine and Maligne Lakes, and both act as reservoirs, storing runoff. This creates a lag time for runoff which should dampen flood peaks on a hydrograph. However, Brown (1970) suggests that small shock wave flood pulses can be identified on a hydrograph of water coming from Maligne Lake. The effect of Medicine Lake on the shape of the Maligne River hydrograph will be discussed below.

TABLE 7

Comparison of the Maligne and Miette Basins

	Maligne	Miette
area	880 km^2 (332 $mi.^2$)	663 km^2 (256 $mi.^2$)
length of river	67.6km (42 mi.)	49.8 km (31 mi.)
elevation of source	2691 m (8500')	1982 m (6500')
elevation of mouth	1036 m (3400')	1036 m (3400')
gradient	23 m km^{-1} (116.6'/mi.)	19 m km^{-1} (100'/mi.)
lakes	Maligne 1774m (5480') Medicine 1449 m (4750')	Miette 1982m (6500')
	Eastern Tributary to the Athabasca River	Western Tributary to the Athabasca River
mean yearly Q	16.09 $m^3 s^{-1}$	11.2 $m^3 s^{-1}$

Figure 25
Miette and Maligne Basin



Discharge data are available for the Maligne River from Water Survey of Canada for the years 1973 to present. Incomplete records are available for the years 1916 to 1920. Table 8 presents basic discharge data for the Maligne River as compared to the Miette. The gauge for the Maligne River is a graphic gas purge pneumometer located immediately down river from the Warden Station and below the cave springs. The Maligne River's mean discharge for the years 1973-1979 is $16.09 m^3 s^{-1}$ (560 cfs). Maximum daily discharge occurs between early July and early August during summer storms which, combined with higher temperatures, produce increased snowmelt. It ranges between $44.2 m^3 s^{-1}$ and $72.8 m^3 s^{-1}$ for these seven years. Minimum daily discharge occurs during the winter between late March and early April and averages $1.8 m^3 s^{-1}$.

3.3 Miette Hydrology

The Miette River was chosen as an analog to the Maligne River. Its behavior is not altered by an underground drainage system as is the Maligne River's behavior. Its dimensions (Table 7) and discharge data (Table 8) are comparable to the Maligne Basin. It is relatively close to the Maligne Basin, located NW of the Maligne Basin across the Athabasca River Valley. The mouths of the two rivers are 10Km apart along the Athabasca whereas the heads are 100Km apart (Figure 25).

TABLE 8

Comparison of Maligne and Miette Discharge Data

Mean Discharge (m^3/s)								
	1973	1974	1975	1976	1977	1978	1979	Mean
Maligne R.	14.45 m^3/s	19.6 m^3/s	14.65 m^3/s	17 m^3/s	17 m^3/s	N.A.	14 m^3/s	16.09 m^3/s (560 cfs)
Miette R.	N.A.	N.A.	N.A.	12.89 m^3/s	10.4 m^3/s	12.49 m^3/s	8.99 m^3/s	11.2 m^3/s (370 cfs)
Total Discharge (X10 m^3)								
	1973	1974	1975	1976	1977	1978	1979	Mean
Maligne R.	455161	579745	461329	534105	535339	N.A.	355087	500613
Miette R.	N.A.	N.A.	N.A.	407055	328111	394720	284000	353471
Maximum Daily Discharge (m^3/s)								
	1973	1974	1975	1976	1977	1978	1979	Mean
Maligne R.	48.1	72.8	46.7	44.2	48.7	N.A.	44.4	51.0 m^3/s
Miette R.	87.28	113.9	46.9	67.4	73.11	81.9	80.3	78.0 m^3/s
Minimum Daily Discharge (m^3/s)								
	1973	1974	1975	1976	1977	1978	1979	Mean
Maligne R.	1.83	2.09	1.8	1.05	1.7	N.A.	2.27	1.8
Miette R.	N.A.	N.A.	N.A.	.538	.569	.46	.4	.5
Maximum Instantaneous Discharge (m^3/s)								
	1973	1974	1975	1976	1977	1978	1979	Mean
Maligne R.	51.0	74.25	49.87	45.06	51.2	N.A.	45.9	53.0
Miette R.	98.8	121.0	52.4	68.01	80.7	87.8	83.9	84.0

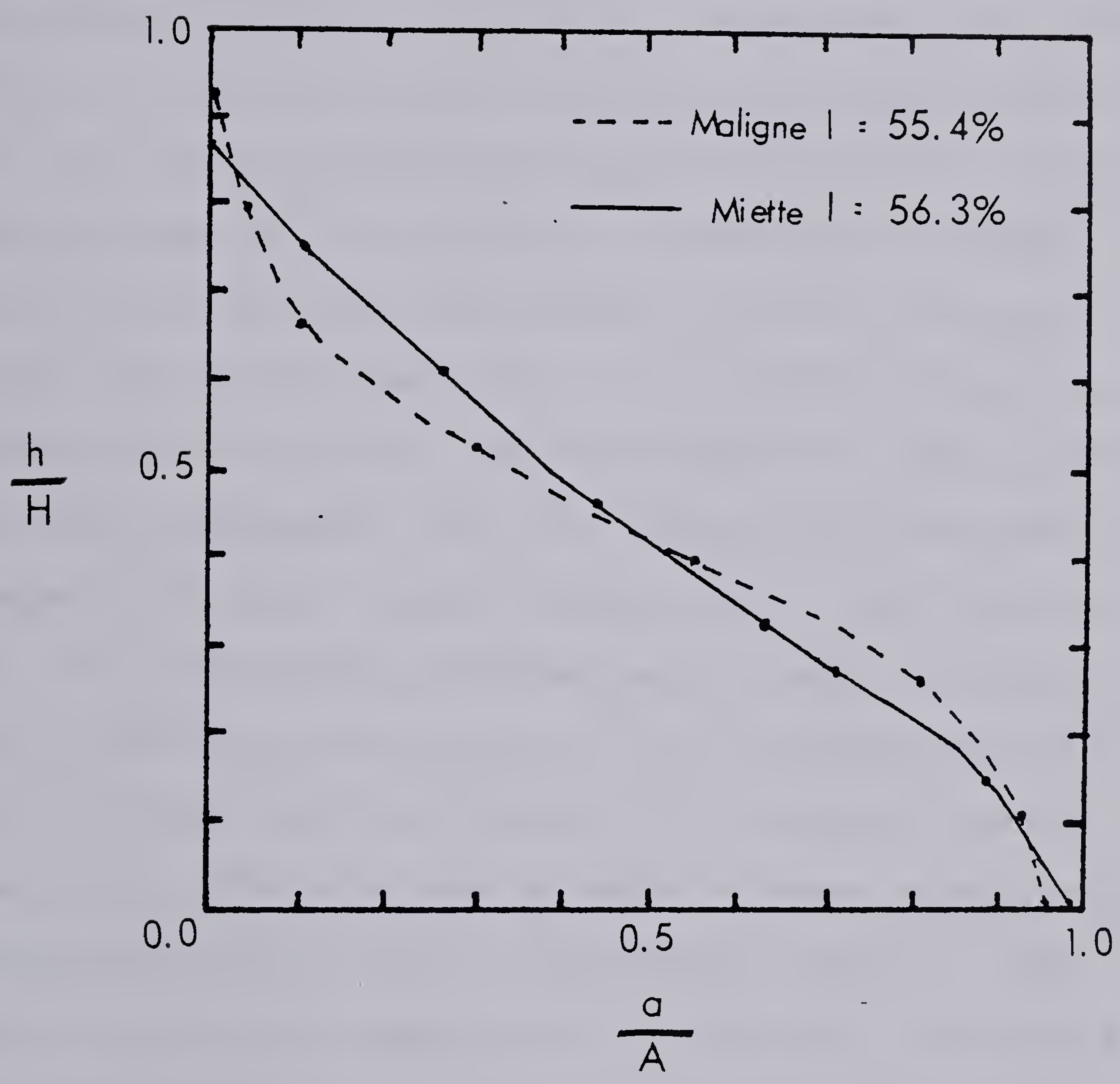
N.A. - data not available

Source: Water Survey of Canada Data

It is proposed that the Miette River is typical of a mountain flow regime. It heads in Miette Lake, a small (300X100m) lake at the continental divide near Miette Pass. The Miette River flows south to Yellowhead Pass where it swings east to flow into the Athabasca River. It drains a basin of 663km^2 (256 mi^2) and has five major tributaries. These are Rink Brook, Deer Creek, Minaga Creek, and two unnamed creeks which enter from the SE portion of the basin. The Miette River flows a total of 50km (31 mi) in the valley between the Continental Ranges on the north and the Park Range of the Rocky Mountains on the south. Its average gradient is 19m km^{-1} (100 ft/mi).

Hypsometric analysis was applied to the two basins to obtain a measure of relief (Strahler, 1952). Figure 26 is a plot of the percentage hypsometric curves for the two basins. These curves indicate that the two basins are similar in their relief-to-area distribution. The Hypsometric Integrals of the two basins further support this similarity. The Miette Integral is 56.3% and the Maligne Integral is 55.4%. The minor differences in the hypsometric curves may be attributed to the fact that the Maligne Valley is a hanging valley while the Miette is not. This gives the larger portion of the drop in elevation for the Miette Basin near the head waters rather than near the mouth as is the case for the Maligne Basin. The hypsometric relief measure supports the comparison of the two basins, holding relief relatively constant.

Figure 26
Hypsometric Curves of the Maligne
and Miette Basins



I= Hypsometric Integral

Discharge data are also available for the Miette River for the years 1973 to present. The recording gauge is located near to the junction of the Miette and Athabasca rivers. The mean discharge for 1973 to 1979 is $11.2 m^3 s^{-1}$ (370 cfs). The Miette River's minimum daily discharge occurs in winter between mid-January and early April and is approximately $0.5 m^3 s^{-1}$ (17 cfs). The maximum daily discharge occurs in June during rain storm periods which accelerate melt of snow to maximize spring surface runoff. Table 8 shows maximum daily discharge is consistently higher for the Miette River but total discharge and mean discharge are higher for the Maligne River. If precipitation was equal between the two basins, the Miette Basin's shape could be partially responsible for this. Using the lemniscate loop as a measure of basin shape (Chorley, Malm, and Pogorzelski, 1957) the relationship between basin length and basin width may be defined as the value k. For the Maligne Basin K=4.07, with 2.94 for the Miette Basin. This measure clearly demonstrates that the Miette Basin is more rounded than the Maligne Basin which would cause storm runoff to peak relatively quickly compared to the Maligne. Possibly a more important influence is the Maligne cave system which will act to dampen runoff peaks. This aspect will be discussed in detail below.

3.4 Hydrograph Presentation, Interpretations

3.4.1 Presentation

Plates 1-7 are hydrographs of the Miette and Maligne Rivers for the years 1973 to 1979. The Maligne discharge is represented by the blue curve and the Miette is represented by the red curve. **The Miette River discharge data have been altered so that the mean discharge equals that of the Maligne for each year.** Table 9 shows the amount altered.

There are very interesting observations to be made about the comparison of the two curves for corresponding years. Both are similar in that they show the expected rise in discharge during the spring melt of May and June. It is interesting to note that most of the minor peaks correlate in both curves although the Miette peaks are somewhat sharper, rising to a higher peak and falling quickly. It is proposed that the correlation of the peaks demonstrates that the two basins are under similar general precipitation and temperature regimes. Figure 27 is a plot of climatic data for Jasper Townsite, located mid-way between the two basins. It is acknowledged that local climates of mountain basins (even those of close proximity) may vary significantly. However, Figure 27 demonstrates that the spring peak discharges of the two rivers closely match the major summer rainstorms recorded at Jasper Townsite, plus high temperature cycles. The late summer-early fall discharge peaks may be attributed to precipitation alone because snow melt has been largely completed by that time.

TABLE 9

Miette Discharge Altered for Hydrographs

	Maligne Mean Q	Miette Mean Q	Miette altered
1973	14.4 m^3s^{-1}	11.8 m^3s^{-1}	+2.6 m^3s^{-1}
1974	28.1 m^3s^{-1}	19.7 m^3s^{-1}	+8.4 m^3s^{-1}
1975	20.6 m^3s^{-1}	13.3 m^3s^{-1}	+7.3 m^3s^{-1}
1976	16.9 m^3s^{-1}	12.8 m^3s^{-1}	+4.0 m^3s^{-1}
1977	17.0 m^3s^{-1}	10.4 m^3s^{-1}	+6.6 m^3s^{-1}
1978	19.2 m^3s^{-1}	12.4 m^3s^{-1}	+6.8 m^3s^{-1}
1979	13.9 m^3s^{-1}	8.9 m^3s^{-1}	+4.9 m^3s^{-1}

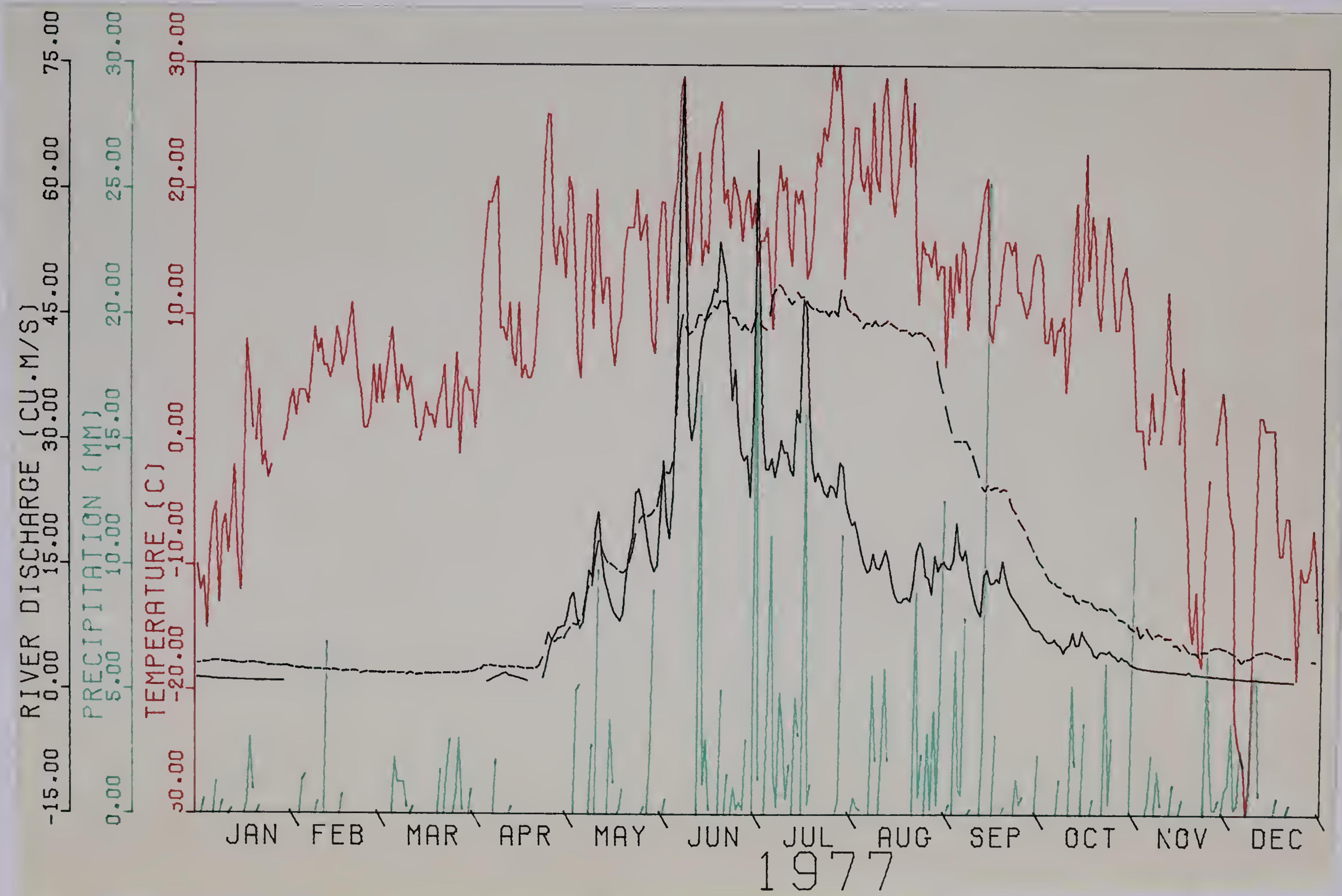


Figure 27 Plot of Jasper Climate Data with Maligne--- and Miette—— Discharge Data

Plates 1-7 reveal a striking contrast between the two curves during the summer months of June to August. During this period, the Maligne River discharge reaches a fairly constant plateau of $42.5m^3s^{-1}$ (1500 cfs) with the exception of minor isolated peaks. At the end of this plateau phase (varying year to year from late August to early October) there is a sharp drop of the Maligne River discharge. For most years the discharge drops within one week to values comparable to those of the Miette River. In contrast to the Maligne plateau, the peak discharge of the Miette River occurs approximately during the third week of June (averaging $77m^3s^{-1}$) and very gradually drops through the next four months.

The difference curve at the top of each hydrograph demonstrates the distinct separation between the two flow regimes. There is a large difference ($>15m^3s^{-1}$, 530 cfs) between the two curves during the months of late May to late August. The Miette River discharge is greater than the Maligne River discharge from late May to late July. At this time the Maligne River discharge becomes greater than for the Miette River, until they equalize again in late August or September.

3.4.2 Interpretation

The Maligne River hydrographs are classic examples of impeded flow. The discharge plateau of $42.5m^3s^{-1}$ (1500 cfs) approximates the full volume carrying capacity of the

Maligne cave (either maximum capacity of the sinks, cave channels or risings) plus the addition of minor surface runoff down-valley from Medicine Lake. Storm and runoff peaks are dampened on this plateau because the majority of surface runoff in the basin will be temporarily stored in Medicine Lake, leaving only runoff down-valley from the sinks to contribute to a peak on the hydrograph. The plateau continues into late July when the Miette River dicharge starts to drop because the cave continues to discharge at its full capacity as it drains Medicine Lake. Discharge drops quickly (within one week) in the late fall when Medicine Lake is almost empty. This drop is much sharper than is characteristic of the Miette River.

Water level graphs of Medicine Lake for the years 1976, 1978, 1979 (Figures 28-30) support the above observations. Medicine Lake begins to fill at the same time the plateau begins on the corresponding hydrograph. The high lake levels correspond to peaks on the hydrograph. Finally the sharp drop of the discharge hydrograph corresponds to the time Medicine Lake becomes nearly empty.

Figure 31 is a Jasper climate and Maligne River discharge plot for 1974. It demonstrates discharge of up to $30m^3s^{-1}$ (100 cfs) above the plateau throughout July. This is an example of discharge during an overflow period of Medicine Lake. Runoff flowed into and out of Medicine Lake via the overflow channel from June 29 to August 13. The high temperatures of June accelerate snow melt and the rainstorm

Figure 28
Medicine Lake Levels 1976
high level August 18 1439.6 m

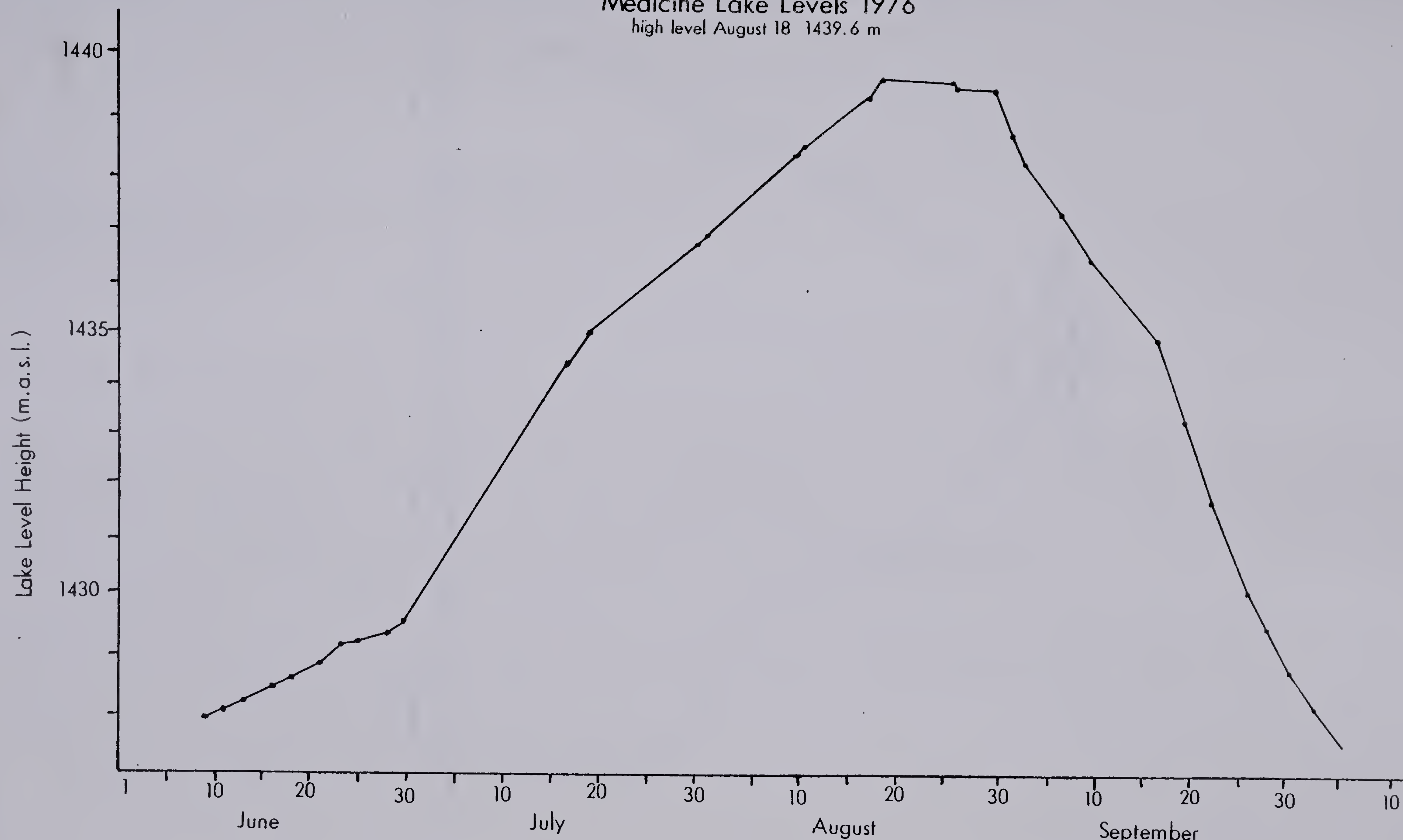


Figure 29
Medicine Lake Levels 1978
overflowing July 14-August 10

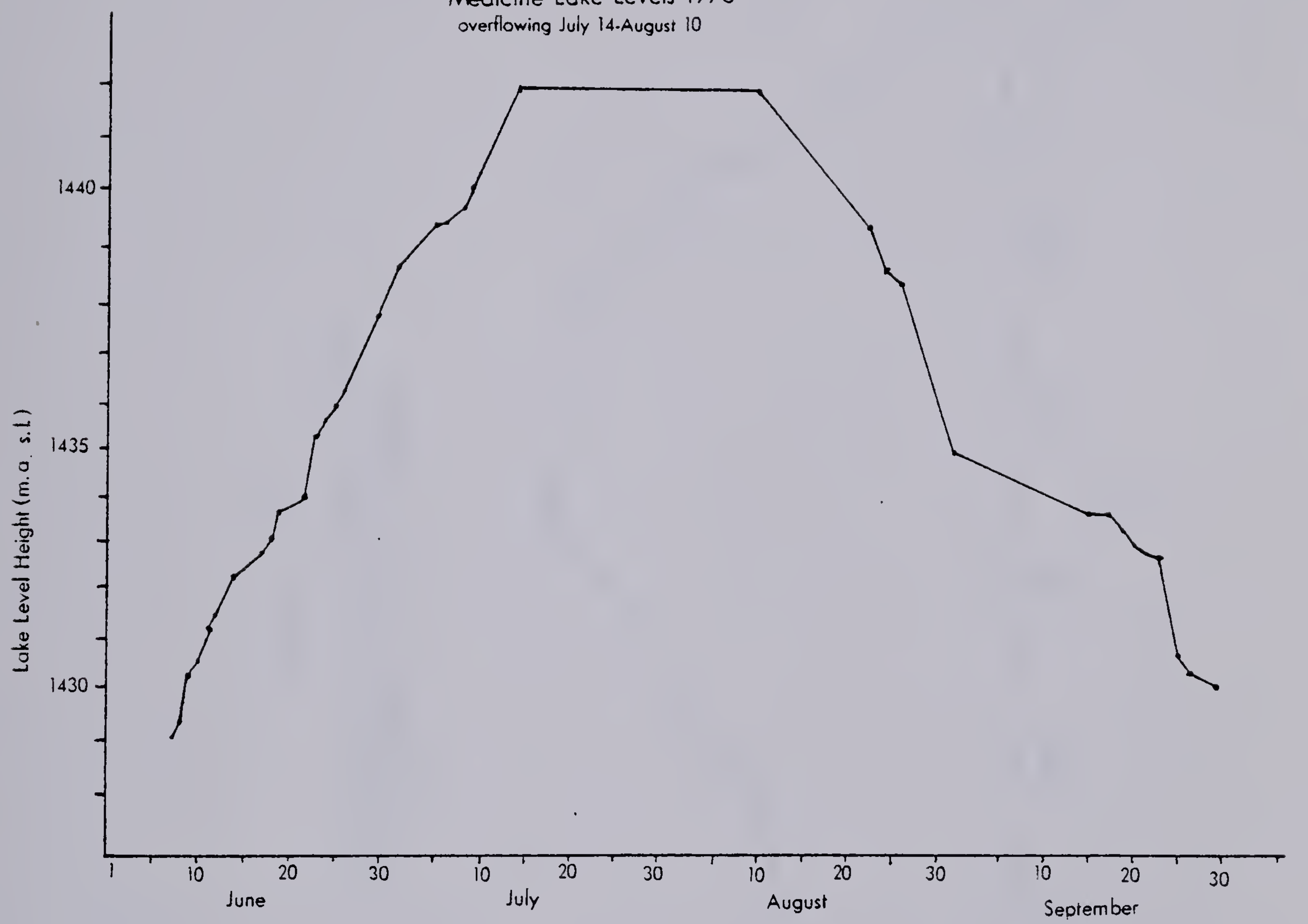
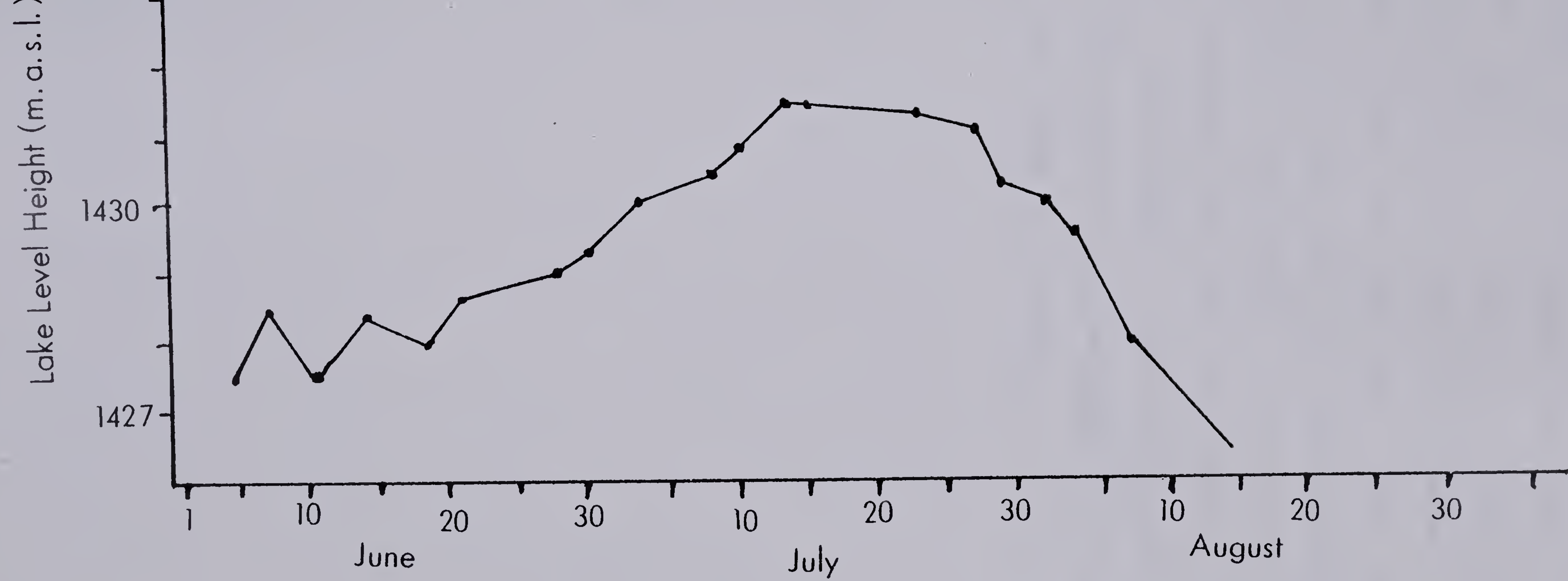


Figure 30
Medicine Lake Levels 1979
high level July 14-15 1431.8 m



during the end of June, and particularly the storm in the second week of July (Figure 31) produced this overflow when the storage capacity of the cave had been exceeded.

It is important to note the magnitude of this overflow, especially as applied to Jasper National Park planning. Mr. C Whitton made available a photograph of an overflow in 1965 (Brown, 1972) which shows a flood from the overflow channel of Medicine Lake of 1.8m in depth. These flood events must be taken into consideration in the development of the basin, ie. the building of buildings and bridges.

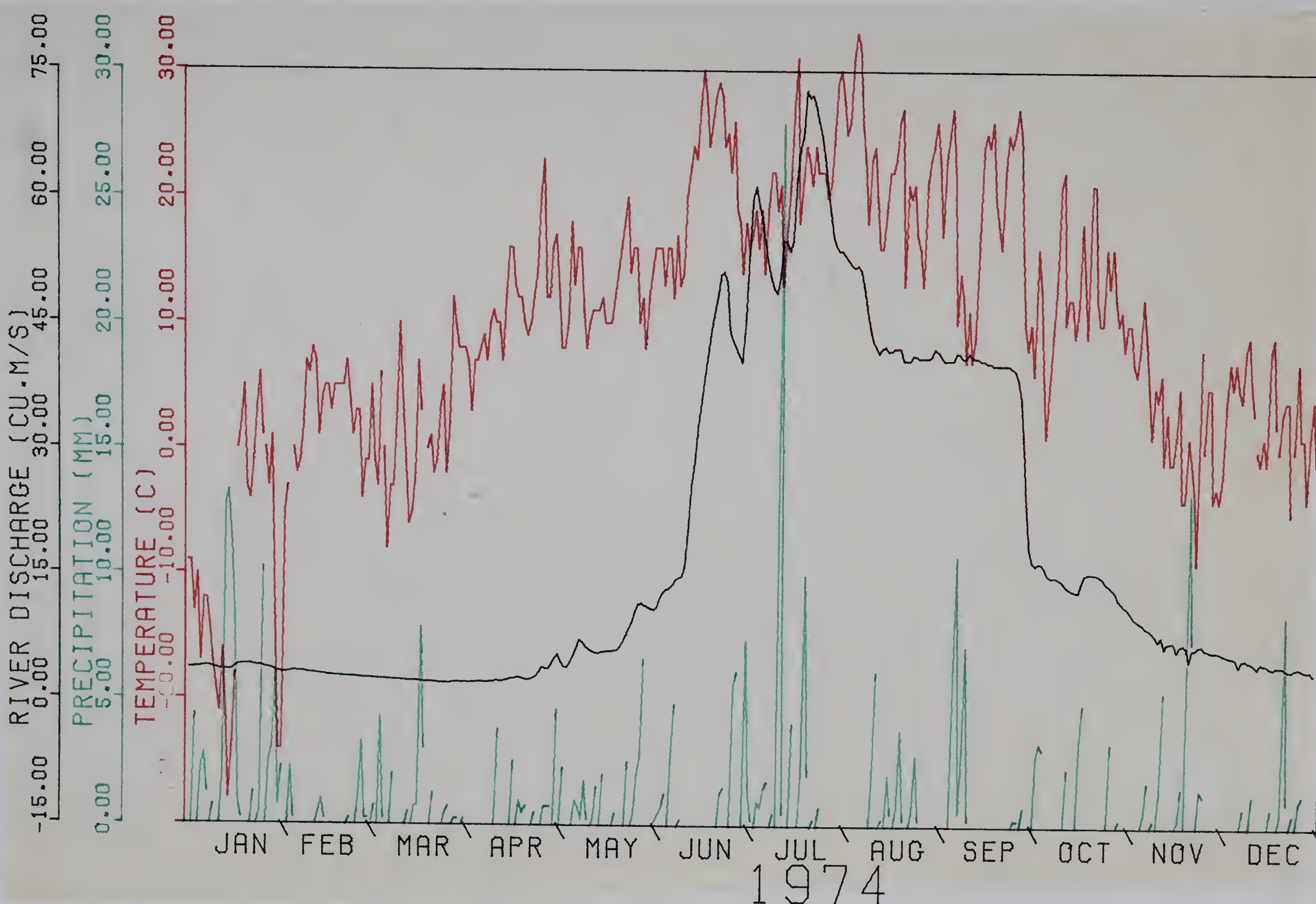


Figure 31 Plot of Jasper Climate Data with Maligne Discharge during Medicine Lake Overflow

4. CHAPTER FOUR, DISCUSSION AND CONCLUSIONS

The Maligne Cave is one of the largest inaccessible caves in the world. The present research combined tracing with hydrograph analysis in order to obtain data to present an updated model of this vast cave system.

The five dye tests, combined with the results from previous dye tests, demonstrate that water entering Medicine Lake sinks in two main places, around the northern end of the lake and halfway up the lake on the northern side. The dye tests have shown that both sink areas have good connections, at all lake levels, to the main springs below Maligne Canyon and the Hatchery Pools at even lower elevations. It has also been confirmed, with dye test 8, that the springs in the bottom of Lac Beauvert represent a previously unrecognized output from Maligne Cave. The discovery of these springs add evidence to support the hypothesis that during the Pleistocene the proto-Athabasca glacier destroyed well developed springs near the old Athabasca River floodplain and covered the opening with fluvial sediments (Ford, 1964). This resulted in the wide dispersion of the present day springs. The Lac Beauvert springs could represent a remnant of the buried pre-Pleistocene output.

The small tributary streams which flow off the valley side into Maligne Canyon were not successfully linked to Medicine Lake. Further research is necessary to determine if these streams do reflect only surface runoff and not cave

springs, despite the fact that they flow out of surface deposits year-round and at a constant temperature.

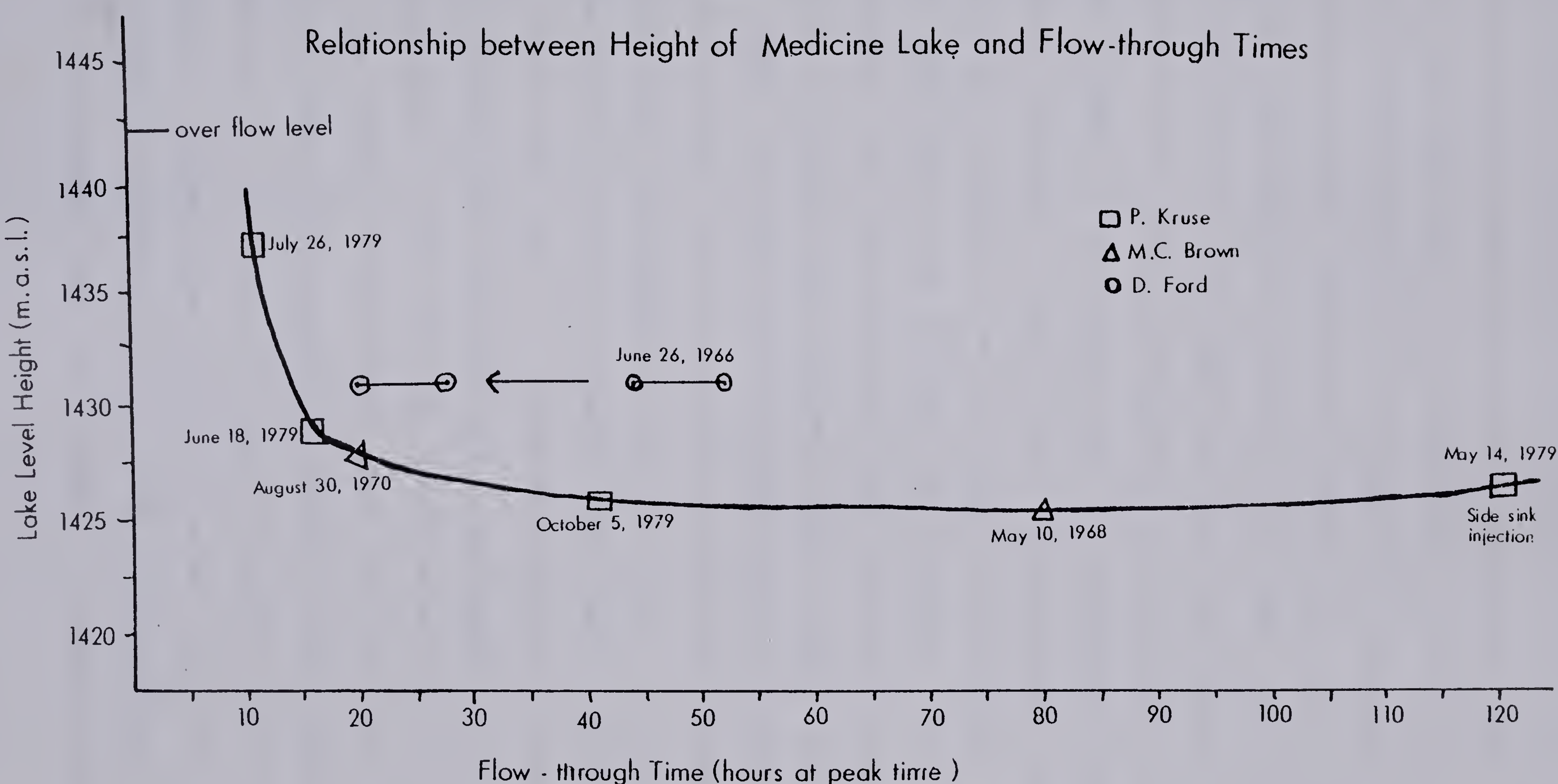
Two new research methods were successfully applied in the present research. Both involved the co-operation of scuba divers. The first was an underwater injection of Rhodamine WT into the side sinks of Medicine Lake. This method allows injection directly into the sinks in order to avoid serious dilution of the tracer before it enters the cave. The second method involved the placement of detectors in the Lac Beauvert lake bottom springs to detect dye before the traced water entered the lake and became further diluted. These inexpensive methods proved particularly useful in Maligne and may be applied anywhere where large amounts of water may easily dilute the tracer beyond detection.

The minimum length of the Maligne Cave, from side sinks of Medicine Lake to the Lac Beauvert springs, is approximately 18.5km. The drop in elevation from the side sinks to the Lac Beauvert springs is 430m. The cave is probably contained within Palliser Formation limestone and follows the strike of the valley.

The flow-through times, indicated by the four successful dye tests completed for the present study, have been combined with the results of earlier tests and plotted against Medicine Lake level in Figure 32. The curve clearly indicates that flow-through time decreases with higher lake stages. The side sinks have flow-through times of greater

Figure 32

Relationship between Height of Medicine Lake and Flow-through Times



than 120 hours at low lake levels. The flow-through time for the main sinks has been established to range between 11 hours at high lake level to 80 hours at low lake level. There is a difference in flow-through times between the May, 1968 and the October, 1979 tests of the main sinks even though the tests were at a similar lake level. The 1979 test was a fall test while the 1968 test was a spring test. The difference in flow-through times may be accounted for by sediment present in the spring that is flushed out during the summer and absent in early fall. This sediment could act to adsorb dye or impede flow to result in the slower flow-through time in the spring. The 11 hours to 120+ hours are extremely fast flow-through times relative to many karst systems of the world (see Bidovec, 1965, Trombe, 1952, Burden, 1963). The cave water has been shown to travel just four hours slower than surface flow at high lake stages. This startling find suggests a very efficient cave system.

The relatively faster flow-through time at higher lake levels may be the result of increased hydrostatic head. Another possibility, which may act simultaneously with increased head, is that the flow could be more diffuse at lower lake levels. At low levels there is less water in the system for chemical and physical erosion on the conduits. As the lake level increases, the amount of water in the cave increases. At higher lake levels the water could flow in more elevated and more efficient conduits resulting in a faster flow-through time. This concept is supported by

Smart's (unpublished) research in Mendip (Brown, pers. comm., 1980). Smart has discovered the consistent presence of a small peak before the main surge of tracer on flow-through curves. He attributes this minor peak to the arrival of water which flows through a more efficient conduit to appear first. The first minor peak present on the Test 8 (Figure 16) flow-through curve may reflect the arrival of flow through this type of more efficient cave passage. An explanation of the presence and significance of one minor peak on a flow-through can not be proven without further research but could be acertained upon entrance into the cave system.

The relatively fast flow-through time indicates that the water is traveling through one or more large conduits rather than traveling with diffuse flow through many fissures and joints. Past statistical research combined with tracer tests on the basin lead to the conclusion that during early spring and late fall the cave is largely air filled (Brown, 1972).

A third explanation of the faster flow-through times at higher lake levels may lie in an examination of the Medicine Lake sinks. Hydrograph analysis revealed a plateau of $42.5 m^3 s^{-1}$ which represents impeded flow throughout most of the summer. This flow occurs when one part of the cave is filled to its carrying capacity. This may be that the capacity of the sink openings is reached, or the cave channels become water filled, or the risings discharge at

full capacity. In the case of Medicine Lake it is most likely that the sink openings are impeded by the landslide debris

Data does not exist on flow-through times of high lake levels. The 11 hour flow-through time was for a lake level just over half full. At a lake level of just under overflow the flow-through time could be even less. On the other hand, if in fact the capacity of the sinks has been reached when discharge reaches $42.5 m^3 s^{-1}$, and no more sinks exist at higher elevations, the flow-through time could not be much shorter.

Figure 33 is a cross sectional model of Maligne Cave. It demonstrates the connections between all known sinks and risings. There are additional inputs in the river valley between Medicine Lake and the springs but these have not yet been precisely located. Mixing will occur between the sinks and risings at all lake levels. Both vertically separate and horizontally separate conduits may converge to produce the mixing. The cave model of Figure 33 is not drawn to scale and all below ground elevations are hypothesized.

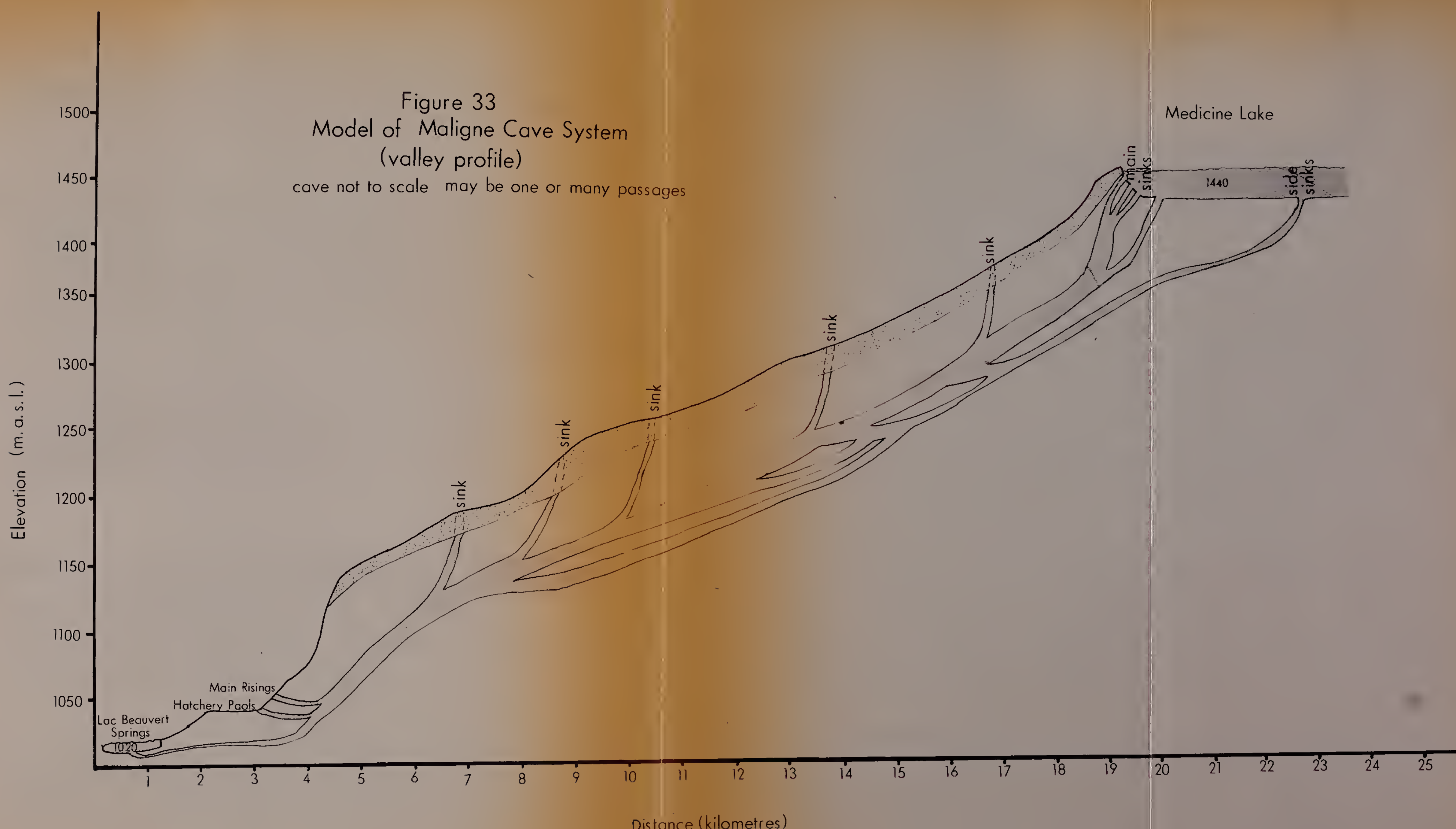


Figure 33
Model of Maligne Cave System
(valley profile)
cave not to scale may be one or many passages
Elevation (m.a.s.l.)
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
Lac Beauvert
Springs
1020
Hatchery Pools
Main Risings
sink
sink
sink
sink
sink
main
sinks
Medicine Lake
1440
side
sinks
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Distance (kilometres)

5. Bibliography

Aley, T., (1963) - Basic hydrographs for subsurface flow in limestone terrain. *Cave Notes* 5(4):26-30.

Arzi, A.A., (1977) - Remote sensing of subsurface karst by micrograviметry. (IN *Karst Hydrogeology*, Memoirs of the 12th congress of the International Association of Hydrologists, Tolson, J.S. and Doyle, ed.) p. 271-272.

Atkinson, T.C., (1968) - Tracing swallet waters using Lycopodium spores. *Cave Research Group of Great Britian, Transactions* 10(2):99-106.

Atkinson, T.C. and D.I. Smith, (1973) - Underground flow rates in cavernous limestones in Britian and Jamaica. *Sixth International Congress of Speleology , Proceedings* Olomouc, Czechoslovakia, p. 13-16.

Ault, D. and P. Hardaway, (1965) - Subsurface tracing with radioisotopes. *Isotopics.*, V. 2:1, p. 1-8.

Back, W. and J. Zoetl, (1975) - Application of geochemical principles, isotopic methodology and artificial tracers to karst hydrology. *Sonderdruck aus Hydrogeology of Karstic Terrains.* CH IX Int. Union of Geological Sciences Series B #3 p. 105-121.

Baird, D.M. (1966) - Jasper National Park - Behind the mountains and glaciers. *Geological Survey of Canada* Report #6, 184p.

Barbier, M. and Poleau, J., (1970) - A pulse compression technique using coherent light. *Geophysical Prospecting 18*, 571-580.

Bidovec, F., (1965) - The investigations of the karst ground water systems and hydrology. *4th International Congress of Speleology, Proceedings* Ljubljana p. 279-285.

Brown, M.C., (1966) - IN *The 1965-1966 Karst Hydrology Expedition to Jamaica, Full Report.* P. Livesey, ed. Privately published, Huddersfield, England. 61 p.

Brown, M.C. and T.M.L. Wigley, (1969) - Simultaneous tracing and gauging to determine water budgets in inacessible karst aquifers. *5th International Congress for Speleology, Proceedings* October, 1969.

Brown, M.C., D.C. Ford and T.M.L. Wigley, (1969) - Water budget studies in karst aquifers. *Journal of Hydrology* 9(1):113-116.

Brown, M.C., (1970) - *Karst Geomorphology and Hydrology of the Lower Maligne Basin, Jasper, Alberta.* PhD dissertation, Dept. of Geog., McMaster University Hamilton, Ontario. 178p.

Brown, M.C. and D.C. Ford, (1971) - Quantitative tracer methods for investigation of karst hydrologic systems, with special reference to the Maligne Basin area, Canada. *Cave Research Group of Great Britian Transactions* 13(1):37-51.

Brown, M.C., (1972) - Karst hydrology of the lower Maligne Basin, Jasper, Alberta. *Cave Studies 13* Cave Research Association, Castro Valley, Ca. 84 p.

Brown, M.C., (1973) - Mass balance and spectral analysis applied to karst hydrologic networks. *Water Recources Research* 9(3):749-752.

Burdon, D.J. ET AL., (1963) - The use of tritium in tracing karst groundwater in Greece. (IN: *International Assoc. of Scientific Hydrology Symposium*, Tokyo, March, 1963): 309-320.

Carston, C.W., (1964) - Use of tritium in hydrologic research-problems and limitations. *International Association of Scientific Hydrology, Bulletin* 9(3):38-42.

Chorley R.J., Malm, D.E.G. and Pogorzelski, H.A., (1957) - A new standard for estimating basin shape. *American Journal of Science* V. 255, p. 138-141.

Corbel, J., (1958) - Climats et morphologie dans la Cordillere Canadienne. *Revue Canadienne de Geographie* 12:16-45.

Cruden, D.M., (1976) - Major rock slides in the rockies. *Canadian Geotechnical Journal* 13(8):8-20.

Drew, D.P., (1968) - A review of the available methods for tracing underground waters. *Proceedings of the British Speleological Assoc.* #6 1968, 19 p.

Drew, D.P. and D.I. Smith, (1968) - Techniques for the tracing of subterranean drainage. *British Geomorphological Research Group, Technical Publication* Series A, 36 p.

Edmonton Geological Society (1964) - Medicine and Maligne Lakes. *6th annual Field Trip Guide Book* 68 p.

Elrick, D.E. and D.W. Lawson (1969) - Tracer techniques in hydrology. *5th Int. Congress for Speleology Proceedings* p. 155-187.

Feuerstein, D.L. and R.E. Selleck, (1963) - Fluorescent tracers for dispersion measurements in surface waters. *California U. Sanitary Engineering Research Lab.* Report

63-1:1-69.

Fischer, H.B., (1968) - Methods for predicting dispersion coefficients in natural streams, with applications to lower reaches of the Green and Ducvamish Rivers, Washington. *United States Geological Survey Professional Paper* 582-A.

Ford, D.C., (1968) - Report to the National and Historic Parks branch on work done under the terms of contract 867. *National Parks Research Collection* 84 p.

Ford, D.C., (1969) - Final report to the National and Historic Parks branch on work carried out under the terms of contract MR324. *National Parks Research Collection* 75 p.

Ford, D.C., (1971) - Final Report to the National and Historic Parks branch on Exploratory Drilling in the lower Maligne Valley, J.N.P. *National Parks Research Collection* 34 p.

Glover, R.R., (1972) - Optical brighteners-a new water tracing reagent. *Transactions, Cave Research Group of Great Britian* 14(2):84-88.

Gregory, K.J., and D.E. Walling, (1973) - *Drainage Basin Form and Process* Edward Arnold, Ltd., 458 p.

Kirk, K.G. and H. Rauch, (1977) - The application of the tri-potential method of resistivity prospecting for ground-water exploration and land use planning in karst terrains. (IN *Karst Hydrogeology, Memoirs of the 12th Congress of the International Association of Hydrogeologists*, Tolson, J.S. and Doyle ed.)

Kirk, K.G. and E.R.Snyder, (1977) - A preliminary investigation on seismic techniques used to locate cavities in karst terrains. (IN *Hydrologic Problems in Karst Regions,* R.R. Dilamarter and S.C. Csallany ed.) p. 70-91.

Manley, T.R. and E.R. Garton, Jr., (1977) - The ABC's of finding and delineating caves with apparent resistivity measurements. *IN Hydrologic Problems in Karst Regions.*

R.R. Dilamarter and S.C. Csallany ed.) p. 92-95.

Maxwell, J.C., (1961) - *Quantitative geomorphology of the San Dimas Experimental Forest, California.* PhD dissertation, Columbia University, New York. 181 pp.

Miller, V.C., (1953) - A quantitative geomorphic study of drainage basin characteristics in the Clinch Mountain area: Virginia and Tennessee. *Office Naval Research Tech. Rept. 3,* Project NR 389-042, Columbia University.

Morisawa, M., (1968) - *Streams, their dynamics and morphology.* McGraw Hill, Inc. 175 p.

Mountjoy, E.W., (1964) - Rocky Mountain front ranges between Rocky River and Medicine Lake, Jasper National Park, Alberta. (IN *Edmonton Geological Society 6th annual Field Trip Guide Book Medicine and Maligne Lakes)* 68 p.

Mountjoy, E.W., (1974) - Maligne Canyon-a story of water erosion since the retreat of the glaciers. *Special Report #2 for Jasper National Park* 22 p.

Mountjoy, E.W., (GSC open file report #372) *Geologic Map of Medicine Lake 83 C/13* .

Newbury, R.W., Cherry, J.A., and Cox R.A., (1969) - Ground water-stream flow systems in the Wilson Creek Experimental Watershed, Manitoba. *Canadian J. Earth Science* 6, 613-23.

Omnes, G. (1977) - High accuracy gravity applied to the detection of karstic cavities. (IN *Karst Hydrogeology, Memoirs of the 12th Int. Congress of the Int. Assoc. of Hydrogeologists* , Tolson, J.S. and Doyle. ed.) p. 273-282.

Palmer, L.S., and Glennie, E.A. (1963) - The geoelectric survey and excavation. IN Tratman, E.K. (ed.)*Reports on the investigation of Pen Park Hole, Bristol* Cave Res. Grp. G.B. pub. 13;15-24.

Parasnis, D.S., (1971) - *Principles of Applied Geophysics* Chapman and Hall, London.

Pilgram, D.H., (1966) - Radioactive tracing of storm runoff on a small catchment. *J. of Hydrology* V. 4 p. 289-326.

Rains, R.B. (1969) - *Some aspects of the Fluvial Geomorphology of the Whitemud Basin, Central Alberta.* PhD. dissertation, Dept. of Geog., U. of Alberta, Edmonton, Alberta 240 p.

Reeder, H.O., (1963) - Tritium used as a ground water tracer between Lake McMillan and Major Johnson springs, Eddy County N. Mex. *U.S. Atomic Energy Commission Report.* TE1-839 120 p.

Replogle, J.A., L.E. Myers, M. ASCE and K.J. Brust (1966) - Flow measurements with fluorescent tracers. *Journal of Hydraulic Division American Society of Civil Engineers Proceedings*, p. 1-14.

Richardson, D.T., (1968) - The use of chemical analysis of cave waters as a method of water tracing and indicator of type of strata traversed. *Cave Research Group of Great Britian Transactions* 10(2):61-72.

Roed, M.A., (1964) - *Geology of the Maligne Valley, Jasper National Park, Alberta.* Research Council of Alberta, Edmonton, Alberta, 44 p.

Scott, C.H., V.U. Norman and F.K. Fields (1969) - Reduction of fluorescence of two tracer tests by contact with a fine sediment. *U.S. Geological Survey, Professional Paper* 650B:164-168.

Sherman, L.K., (1932) - Stream flow from rainfall by the unit-graph method. *Engineering News Record* 108, p. 501-5.

Smart, P.L., (1972) - *A Laboratory Evaluation of the use of Activated Carbon for the Detection of the Tracer dye-Rhodamine WT.* MSc. thesis, Dept. of Geog., U. of Alberta, Edmonton, Alberta , 118 p.

Smart, P.L. and M.C. Brown, (1973) - The use of activated carbon for the detection of the tracer dye Rhodamine WT. *Int. Speleology (1973) III* subsection Cb: Geographical factors in karst erosion, p. 285-292.

Smart, P.L. and I.M.S. Laidlaw, (1977) - An Evaluation of some Fluorescent Dyes for Water Tracing. *Water Resources Research* 13(1):15-33.

Strahler, A.N., (1952) - Hypsometric (area altitude) analysis of erosional topography. *Geol. Soc. Amer. Bull.*, Vol. 63, p. 1117-1142.

Thompson, P., (1975) - In search of the Maligne master cave. *The Canadian Caver* 7(1):57-60.

Thompson, P. (1976) - Caves of the southern Canadian Rockies IN *Cave Exploration in Canada* The Canadian Caver Magazine, P. Thompson ed. p. 120-126.

Trombe, F., (1952) - *Traite de Speleologie* Biblioteque Scientifique, Payot, Paris, 375 p.

White, W.B. and V.A. Schmidt (1966) - Hydrology of a karst area in East Central West Virginia. *Water Resources Research* 2(3):549-560.

Wilson, J.F.,Jr., (1968a) - Fluorometric procedures for dye tracing. *Techniques of Water Resources Investigations of the U.S. Geological Survey* Bk 3, ch A-12:31 p.

Wilson, J.F., Jr., (1968b) - Time of travel measurements and other applications of dye tracing. *International Assoc. of Scientific Hydrology Publication* 76:253-262.

Wilson, J.F.,Jr., and W.E. Forrest, (1964) - Potomac River Time-of-Travel measurements. *Symposium on Diffusion in oceans and Groundwaters Proceedings* p. 1-18.

Wilcock, J.D., (1965) - Geophysical Survey and results; Oxford University Expedition to Northern Spain 1961 *Trans. Cave Res. Grp. G.B., publication* 14, 31-38.

APPENDIX 1

Medicine Lake High Levels 1947 to 1979

Year	Date of Highest Level	Height (above arbitrary datum)
1947	July 20-22	9.9 m (32.8')
1948	June, August	* *
1949	N.A.	N.A.
1950	July 2	18.5 m (60.75')
1951	July 24	7.9 m (26')
1952	July 18	8.9 m (29.5')
1953	July 26	15.47 m (50.75')
1954	July 17	18.9 m (62') *
1955	July 16	18.9 m (62') *
1956	July 1	9.7 m (32')
1957	June 14	7.0 m (23')
1958	July 8	7.4 m (24.5')
1959	July 28	12.13 m (39.8')
1960	July 19	17.5 m (57.5')
1961	N.A.	N.A.
1962	N.A.	N.A.
1963	N.A.	N.A.
1964	July 12-19	*
1965	July 9-August 18	*
1966	N.A.	11.2 m (37')
1967	July 16-August 5	N.A.
1968	July 13,31,August 11	N.A.
1969	N.A.	N.A.
1970	N.A.	N.A.

Year	Date of Highest Level	Height (above arbitrary datum)
1971	August 1	N.A.
1972	June 27-July 23	N.A. *
1973	N.A.	N.A.
1974	June 29-August 13	14.3 m (47') *
1975	N.A.	N.A.
1976	August 18	1439.3 m (4722') new poles (surveyed)
1977	N.A.	1433.3 m (4702')
1978	July 14-August 10	1441.7 m (4730') *
1979	July 14-24	1436.9 m (4713.2')

N.A. Data not available

* overflow year

Source: Jasper National Park Library File, no source given

APPENDIX 2

Automatic Sampler Serial #267, Type #48

This sampler has 24 sample bottles which connect to 24 individual tubes, the ends of which were placed in the river. The bottles are evacuated of air and a vacuum is created. The timer on the sampler has an arm which swings around and opens gates to the bottles. One sample is taken every hour. This method is much more efficient than continuous hand samples as the sampler needs to be manned only once per day, to empty and clean the bottles and create the vacuum; however, the lines are not purged, as with some samplers.

APPENDIX 3

Optical System of the Turner Fluorometer

Figure 34 demonstrates the optical system of a Turner III Fluorometer. Maximum fluorescence intensity occurs at a longer wave length than maximum absorbance for each sample so that the intensity of the emmitted fluorescence can be separated from the excitation spectra by the two color systems. The primary filter on the external light source side of the sample passes only that spectra shorter than the fluorescent wave lengths. The secondary filter on the direction side of the sample passes only the desired fluorescence spectra (Feuerstein and Selleck, 1963).

Four different sized appertures (1X, 3X, 10X, 30X) shelter the relative amounts of light entering the sample, the relative fluorescence intensity. More light is needed for lower dye concentrations.

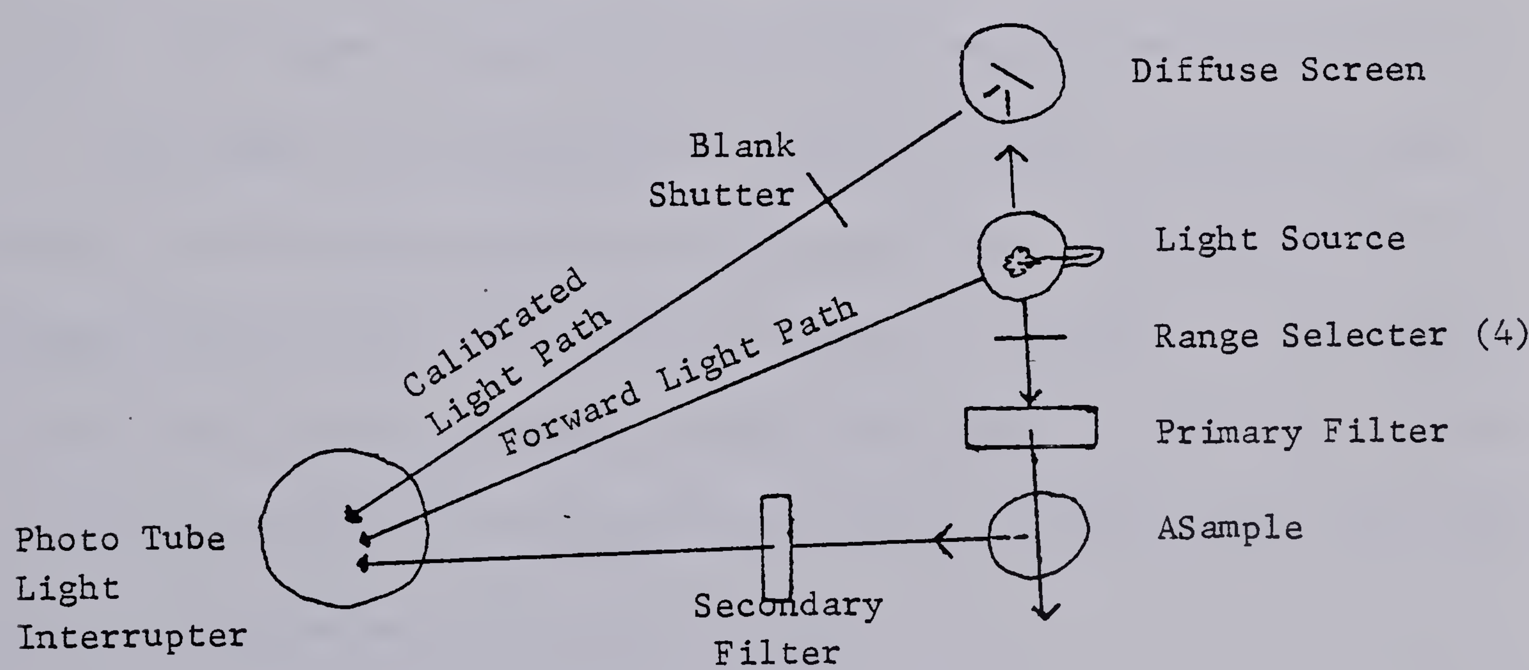


Figure 34

Optical System of a Fluorometer

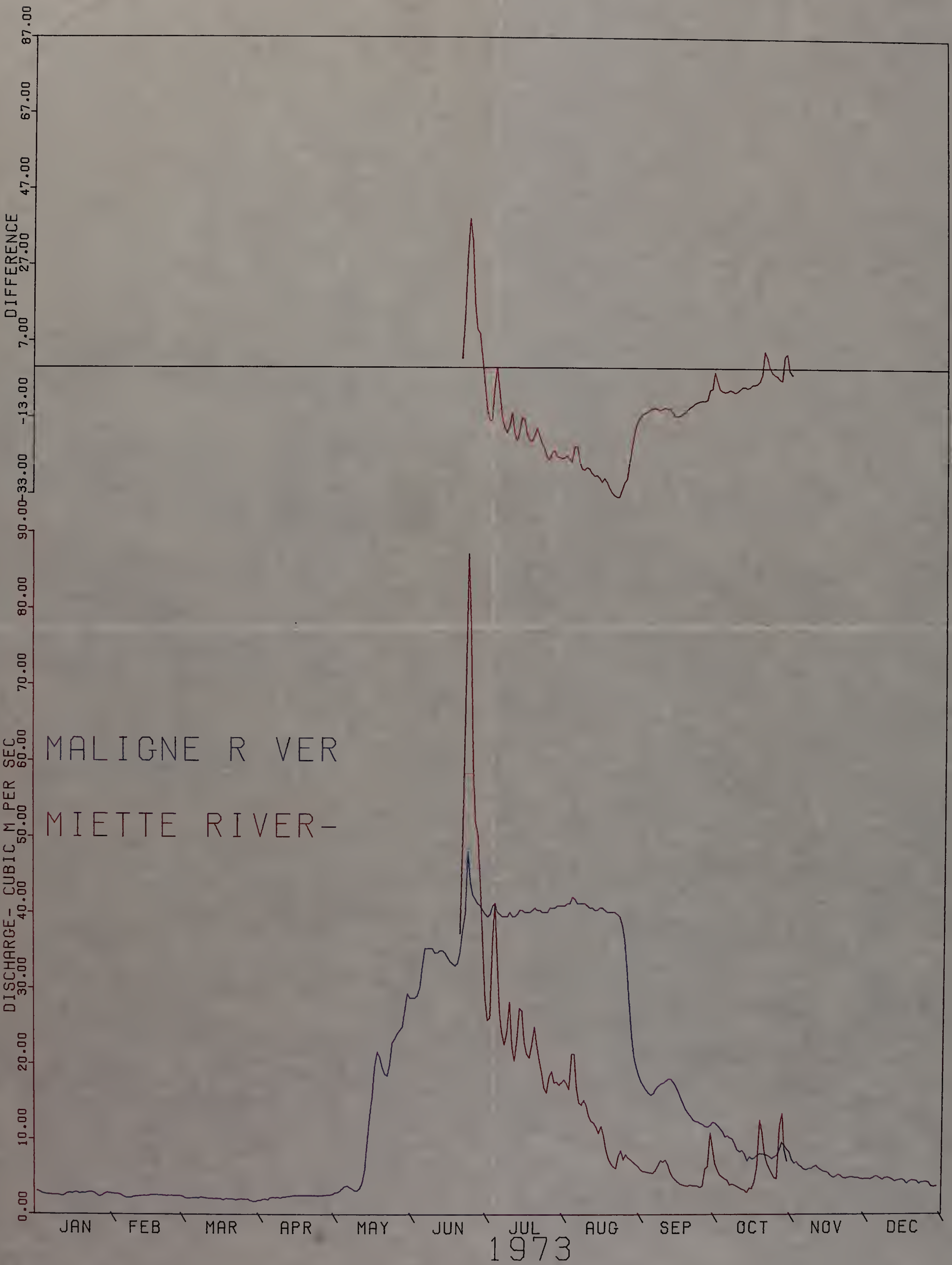
Source: Feuerstein and Selleck, 1963

APPENDIX 4

Underwater Injection Procedures

At high lake levels the side sinks are not visible from the surface. Using photos taken during the May, 1979 test of the side sinks, the approximate location of the sinks was determined. J. Todgham then dove to examine the lake bottom and locate the sinks. The best defined sink was located under 7 m of water. The tracer was poured into a double layered plastic garbage bag. This was dragged by a line to the location above the sink. The outer bag was punctured by a knife tied to the end of a 2 m (6') pole. This released the trapped air and the bag was lowered to the sink. Then the inner bag was punctured and the dye released. The flow carried the dye down into the sink. It did not dilute out into the lake, nor did it become visible from the surface. The plastic bags were picked up months later when the lake level had fallen and the sinks were exposed.

The danger of contamination during the injection was high, therefore, the following steps were taken to avoid it. The diving suit was soaked and the water tested for fluorescence. In addition, the diving gloves were soaked separately and the water tested. The results of the precautionary tests were negative and we were confident that there would be no contamination with further diving.



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DISCHARGE- CUBIC M PER SEC
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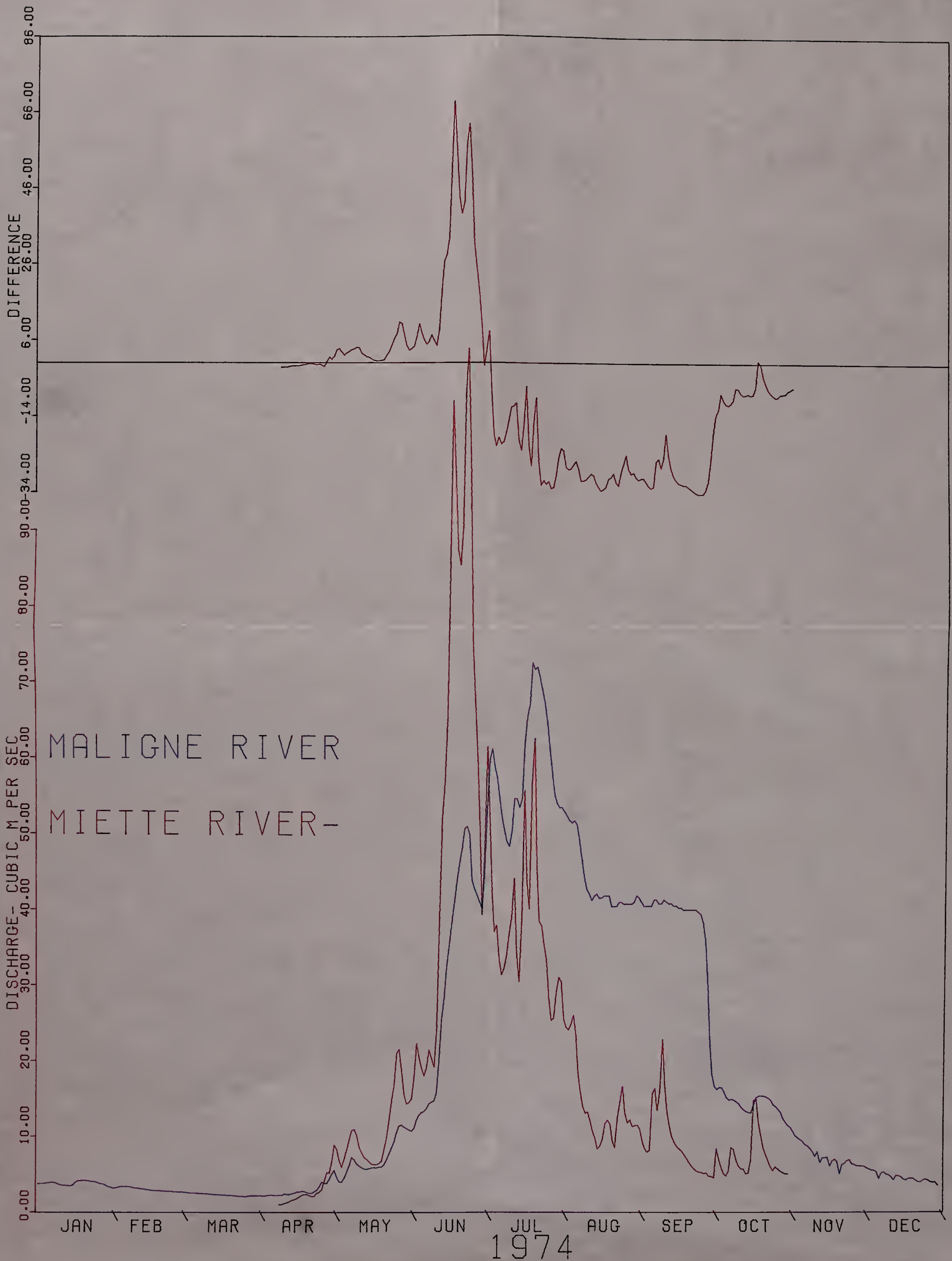
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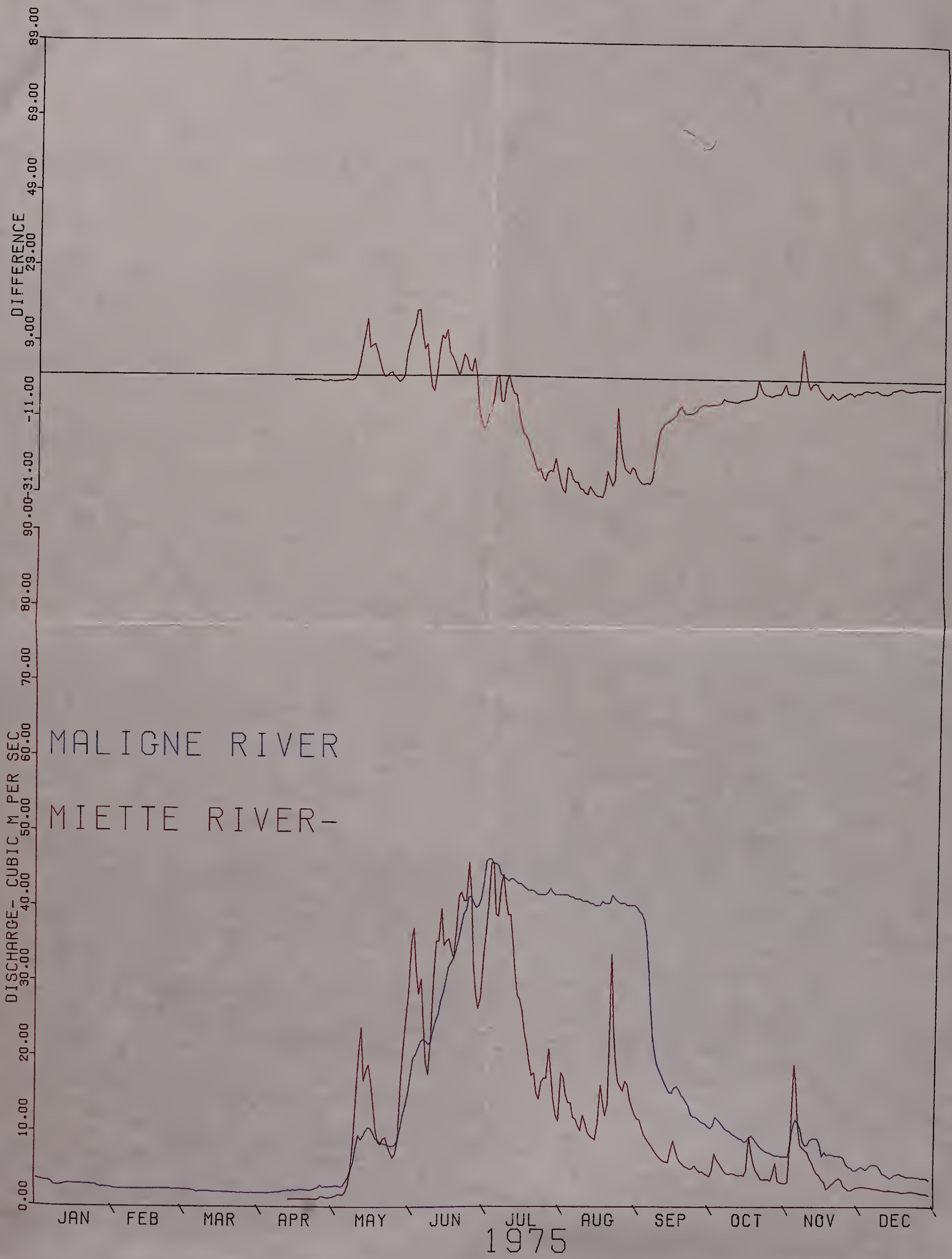
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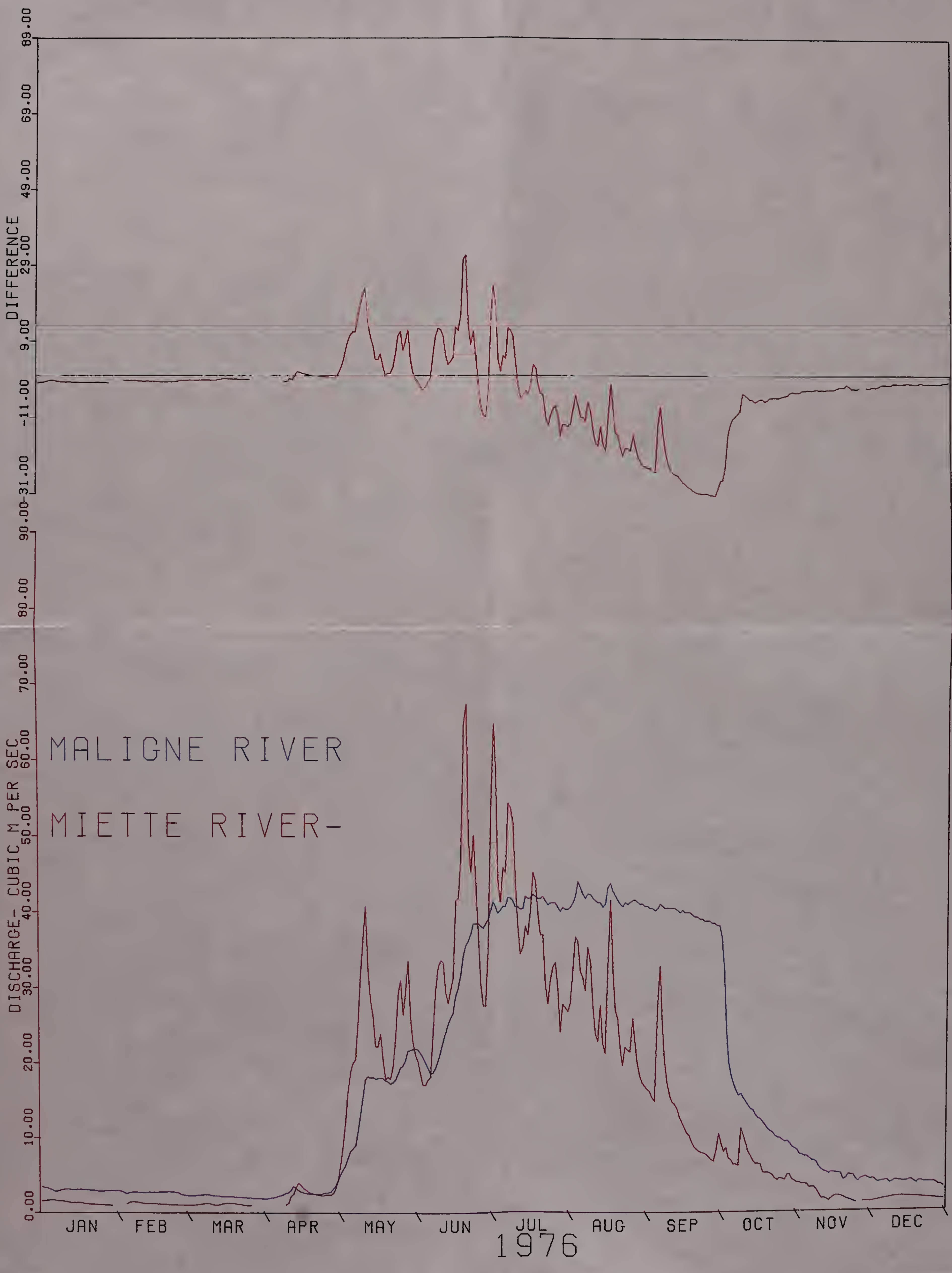

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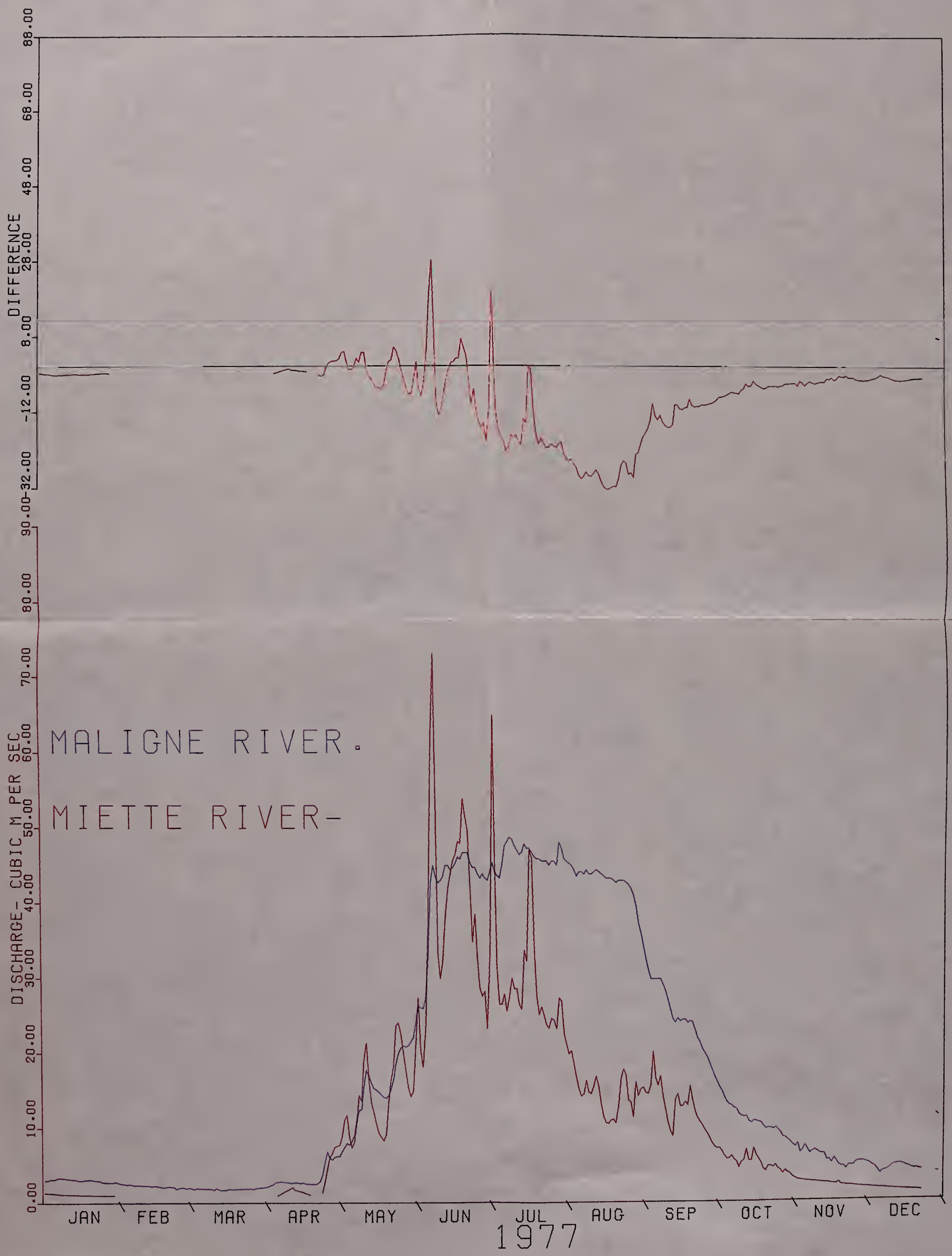

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DISCHARGE- CUBIC M PER SEC
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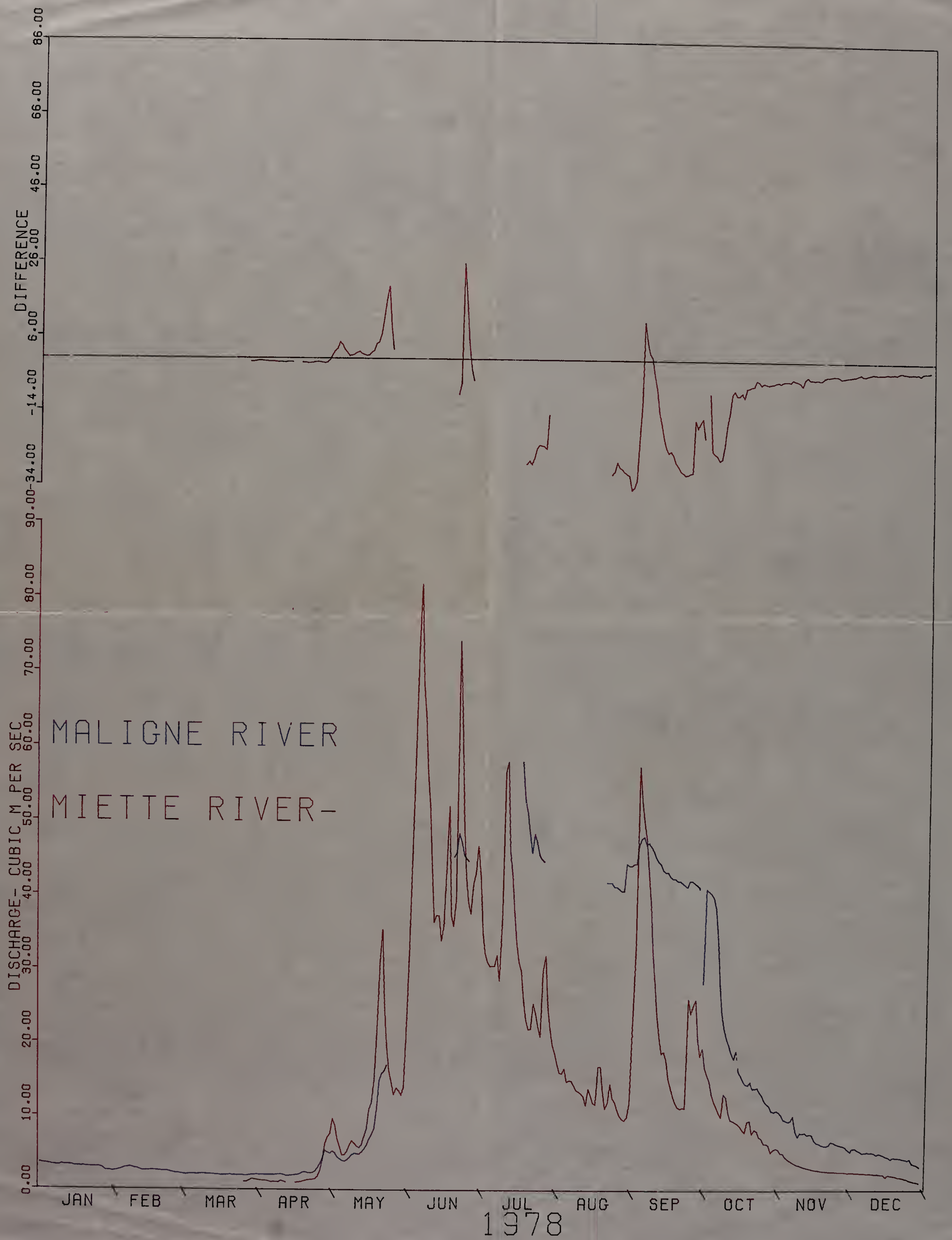
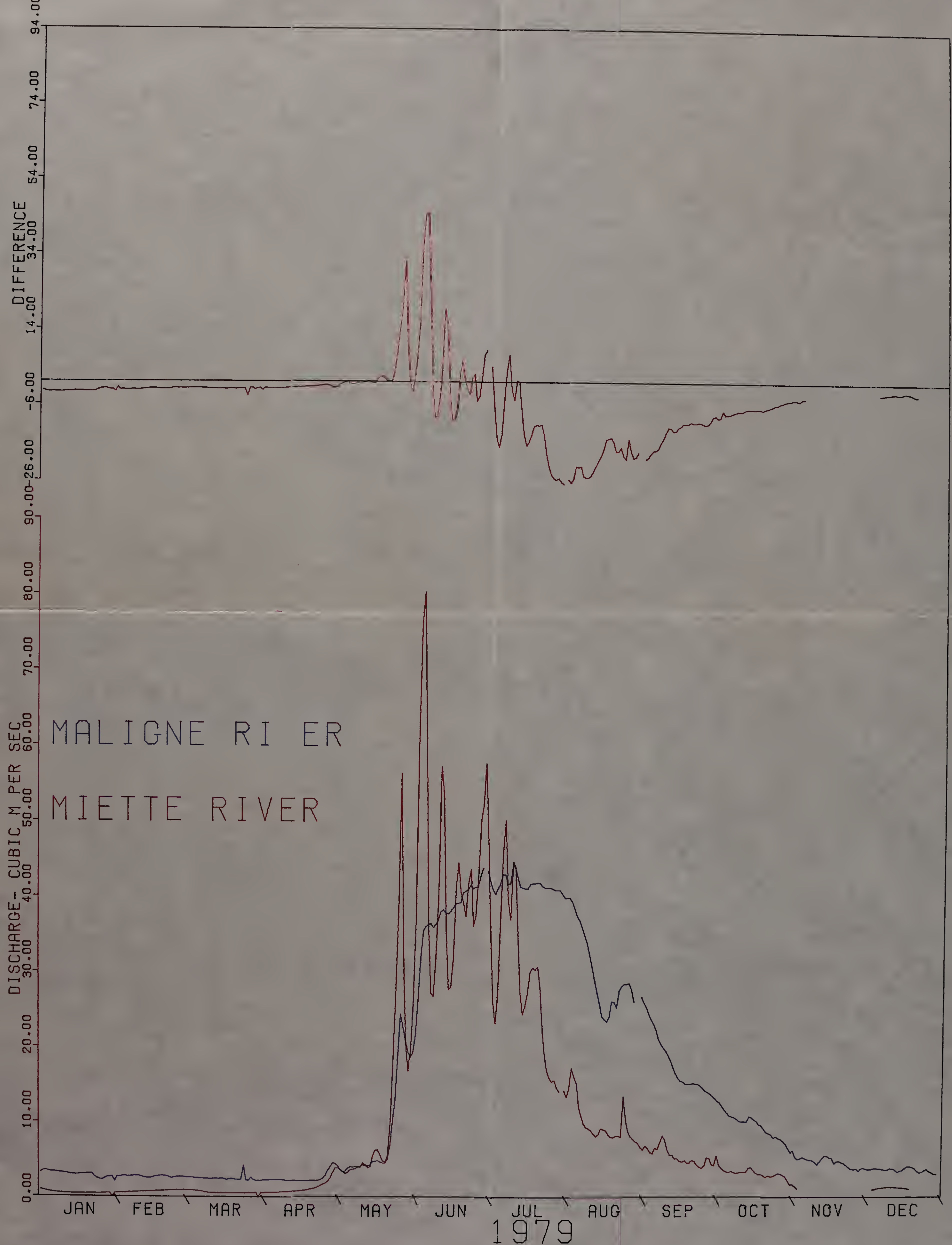
DEC
1977



DIFFERENCE
86.00
66.00
46.00
26.00
6.00
-14.00
-34.00
DISCHARGE- CUBIC M PER SEC
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
MALIGNE RIVER
MIETTE RIVER-
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
1978



DIFFERENCE
94.00
74.00
54.00
34.00
14.00
-6.00
-26.00
DISCHARGE- CUBIC M PER SEC
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
MALIGNE RI ER
MIETTE RIVER
JAN
FEB
MAR
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DEC
1979

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